Einführung in Visual Computing

186.822

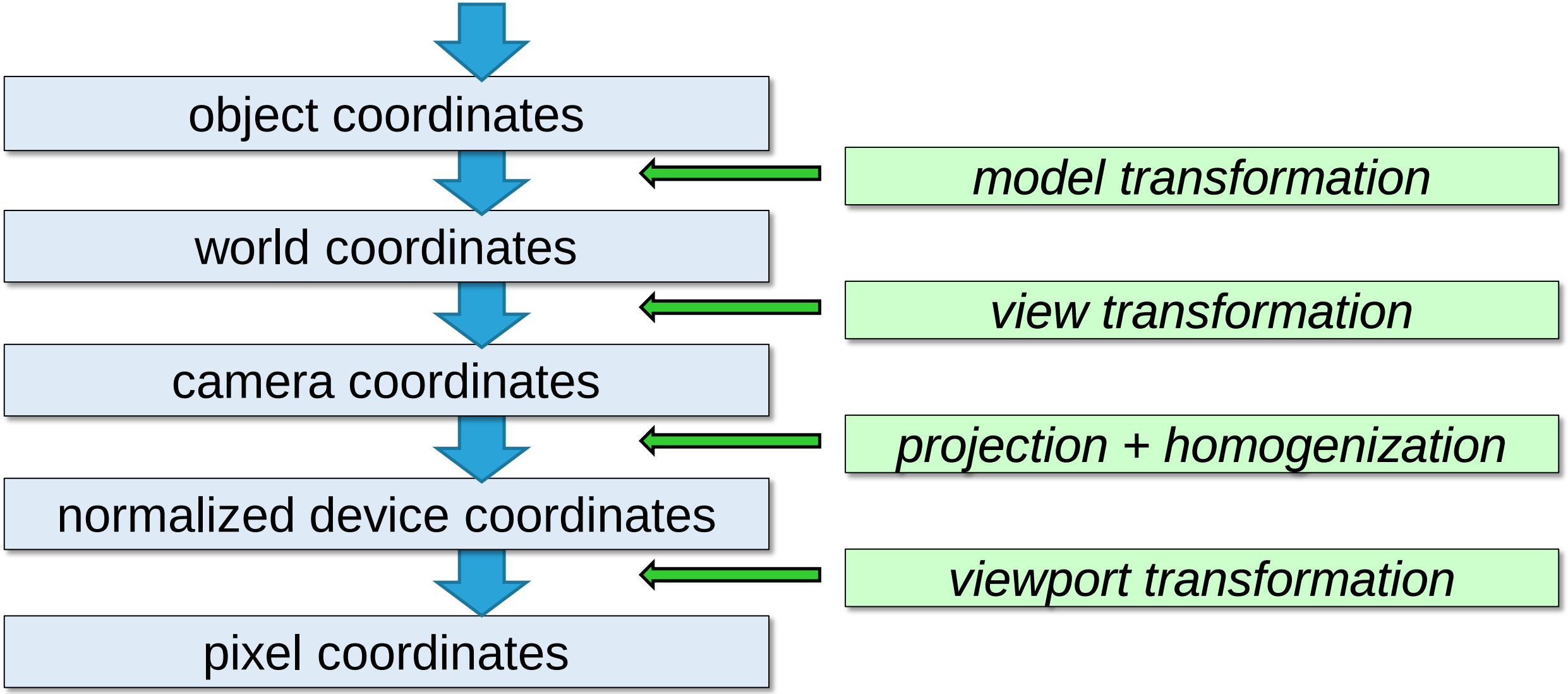
Graphics Pipeline

Werner Purgathofer

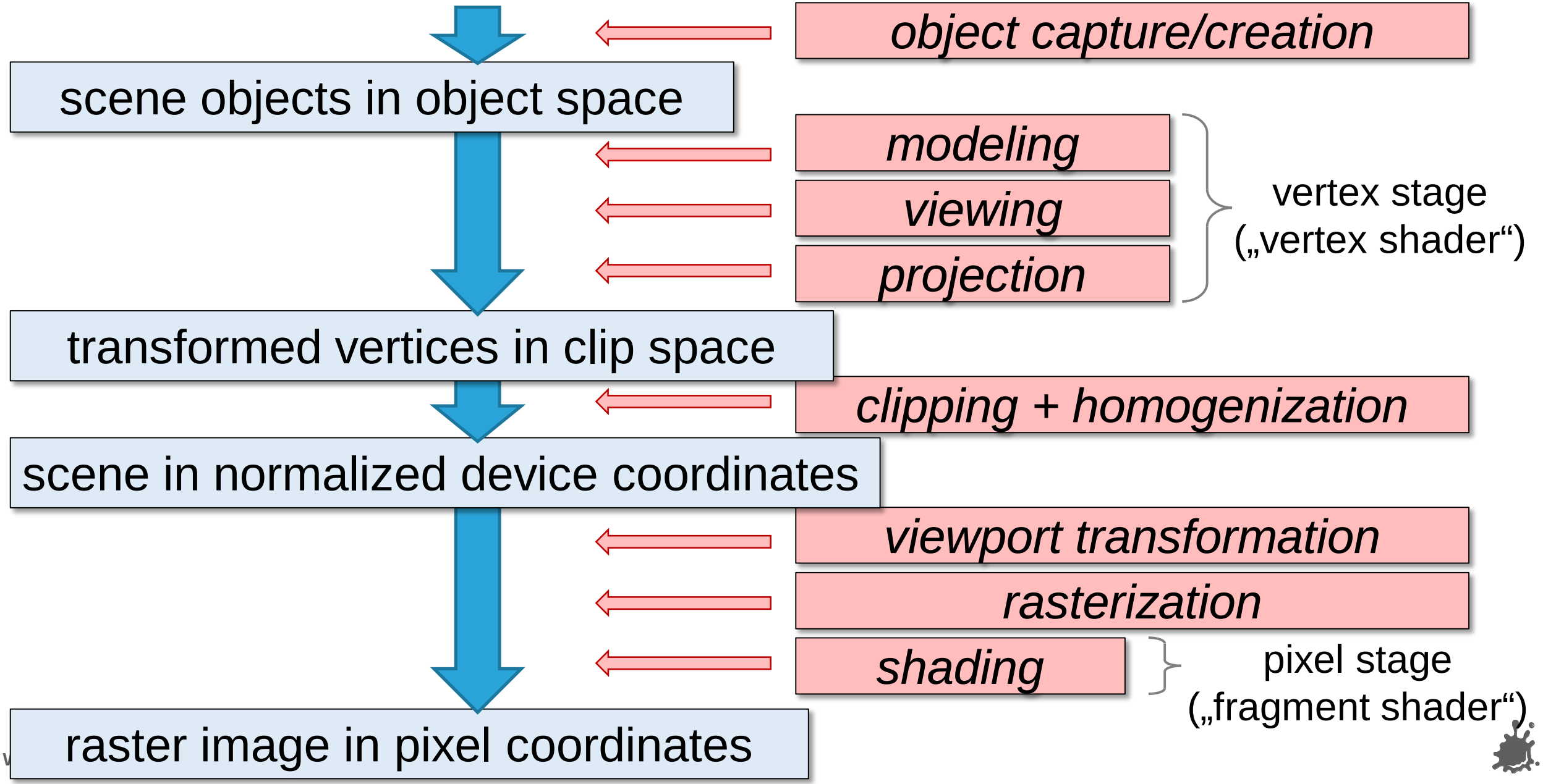
Graphics Pipeline

- information is transformed to an image in successive steps
  - object and scene creation
  - definition of view (camera)
  - projection
  - rasterization
- this is called the ***graphics pipeline***
  (or ***viewing*** *pipeline,* ***transformation*** *pipeline,* ***rendering*** *pipeline, …*)

Transformation Pipeline



Rendering Pipeline (Technical Implementation)



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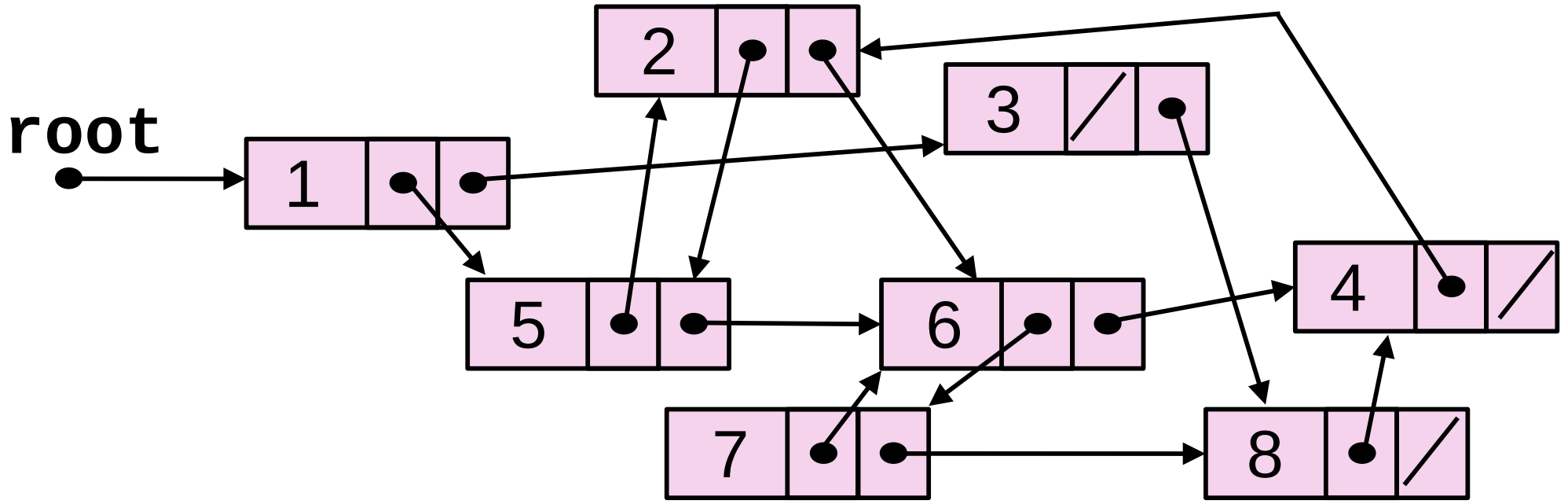
Graphics Pipeline

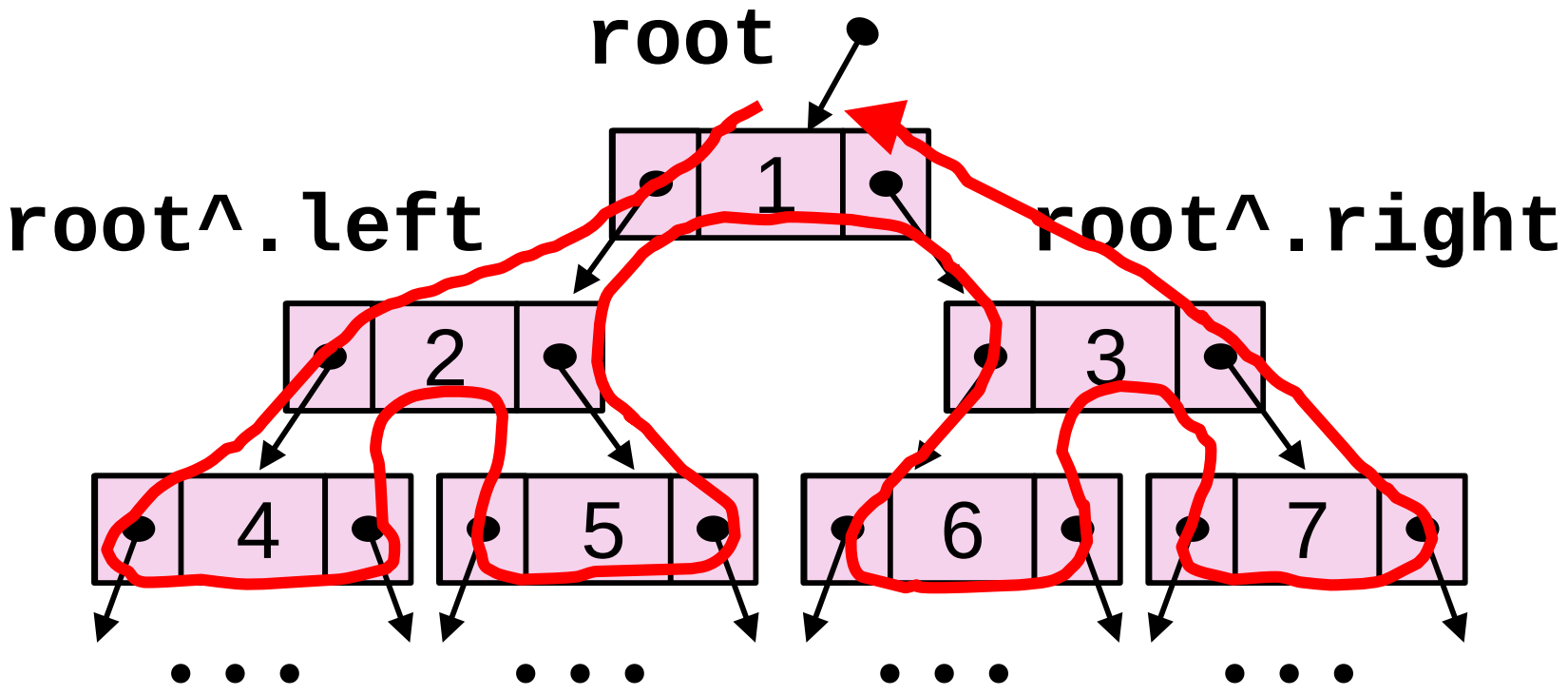
The End

Reminder: Graphs and Trees



arbitrary graph implemented with pointers

Reminder: Graphs and Trees



binary tree implemented with pointers

+ recursive evaluation	*“pre-order”:*	*node-left-right*	*1-2-4-5-3-6-7*
	“in-order”:	*left-node-right*	*4-2-5-1-6-3-7*
	“post-order”:	*left-right-node*	*4-5-2-6-7-3-1*

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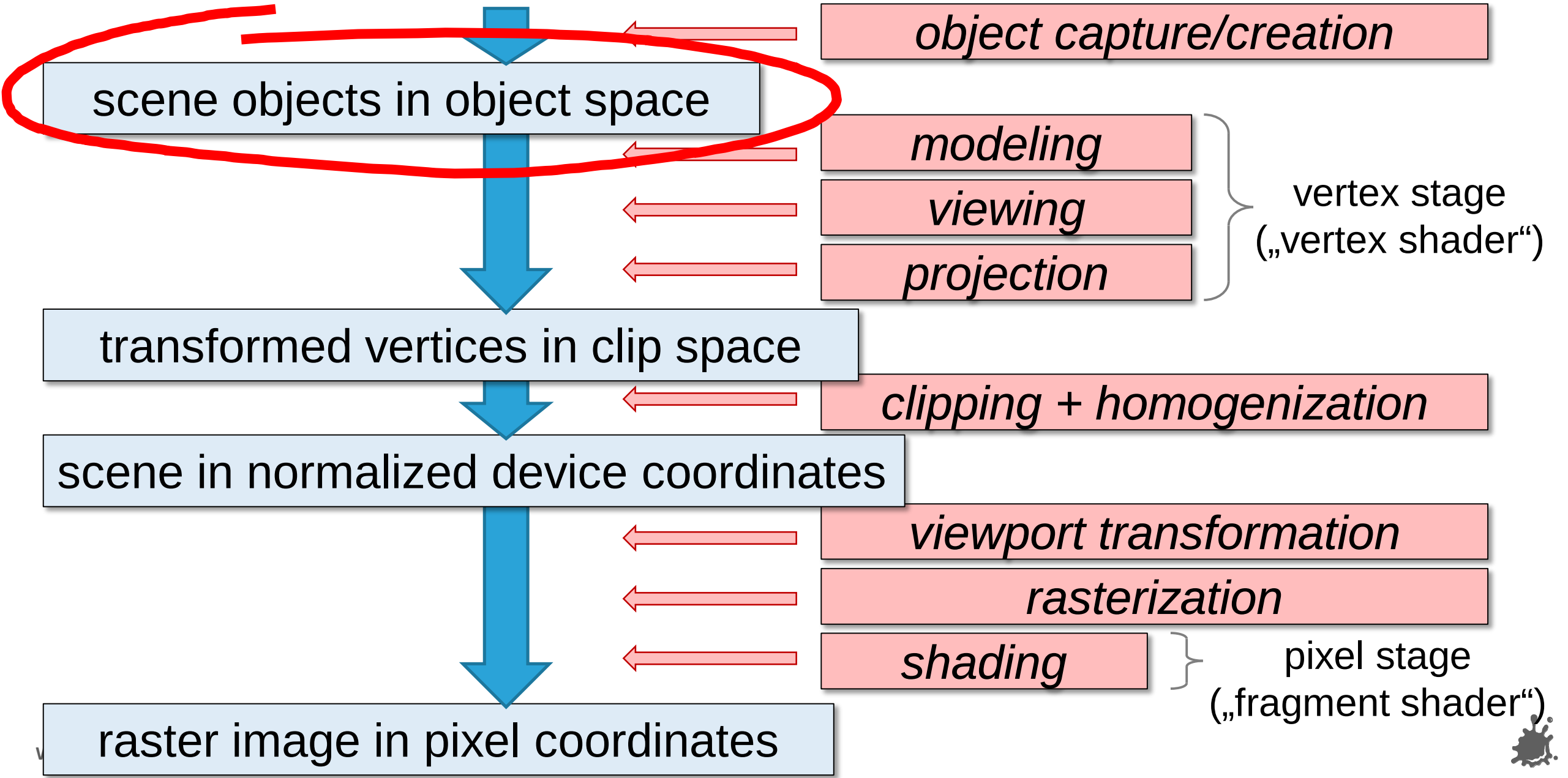
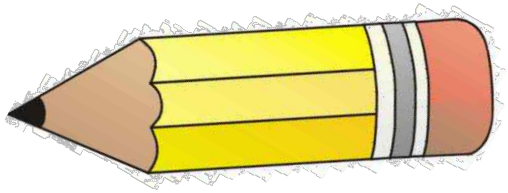
3D Object Representations

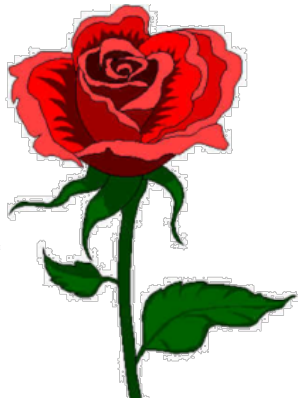
Object Representation in the Rendering Pipeline

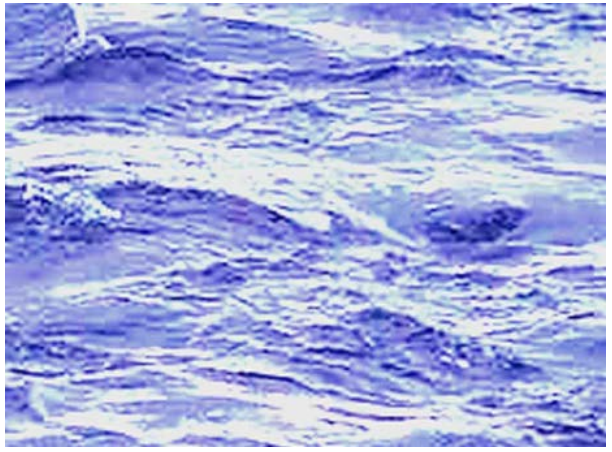


3D Object Representations

- graphics scenes contain
  - solid geometric objects
  - trees, flowers, clouds, rocks, water,…
- creation of models
  - surface ↔ interior models
  - explicit ↔ procedural models
  - heuristically ↔ physically based models
- representations
  - geometrical data structures
  - data structure organization

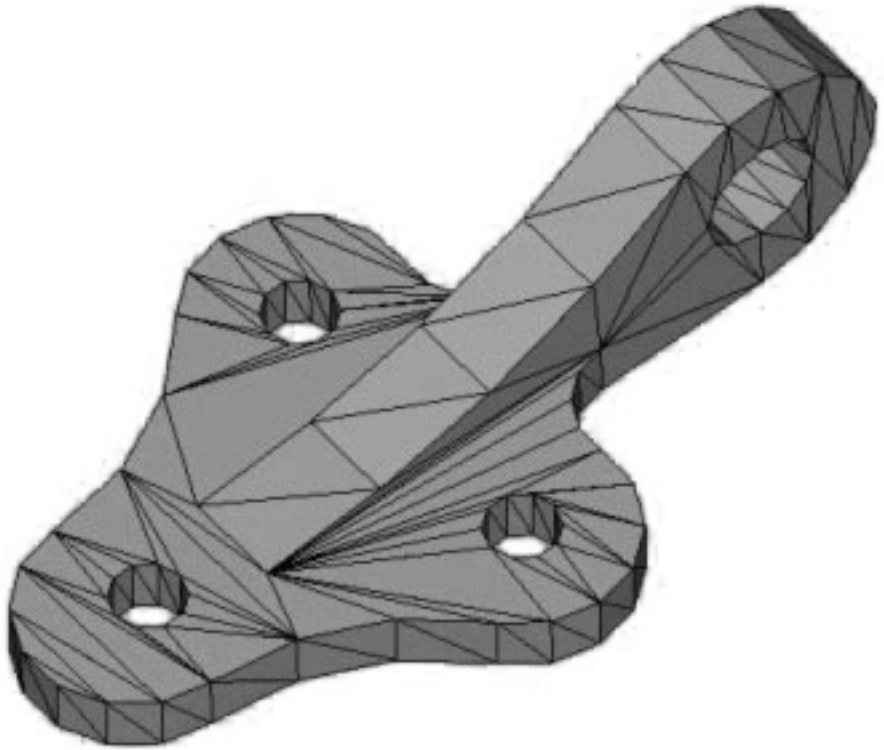




Polygon Surfaces (1)

- set of surface polygons enclose object interior
  = ***Boundary Representation***
  ("B-Rep")



example:
machine part surface
represented by triangles

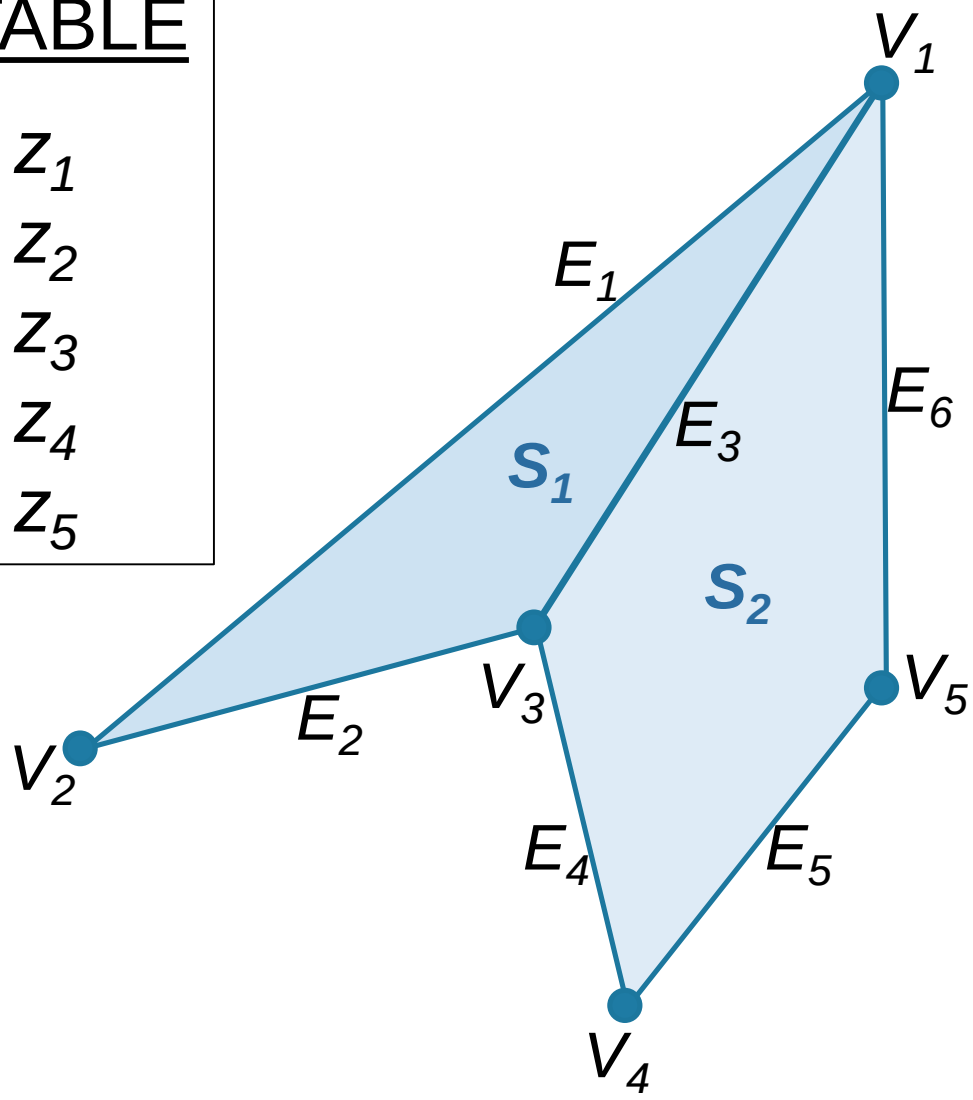
Polygon Surfaces (2)

- polygon tables (B-Rep lists)
  - geometric and attribute tables
  - vertex, edge, polygon tables
  - consistency, completeness checks

Polygon Surfaces: Data Structure

VERTEX TABLE

V_1: x_1, y_1, z_1
V_2: x_2, y_2, z_2
V_3: x_3, y_3, z_3
V_4: x_4, y_4, z_4
V_5: x_5, y_5, z_5



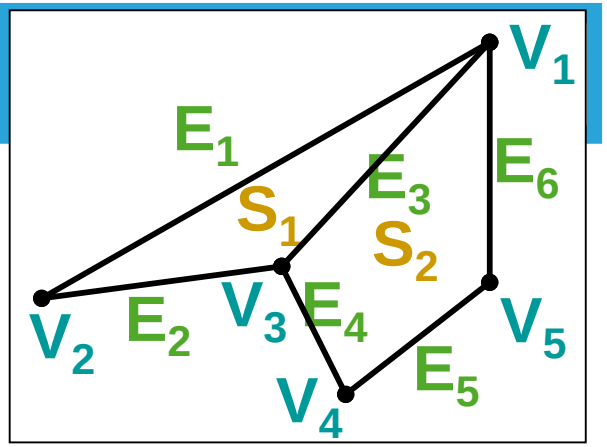
EDGE TABLE

E_1: V_1, V_2
E_2: V_2, V_3
E_3: V_3, V_1
E_4: V_3, V_4
E_5: V_4, V_5
E_6: V_5, V_1

POLYGON TABLE

S_1: E_1, E_2, E_3
S_2: E_3, E_4, E_5, E_6

Lists for B-Reps

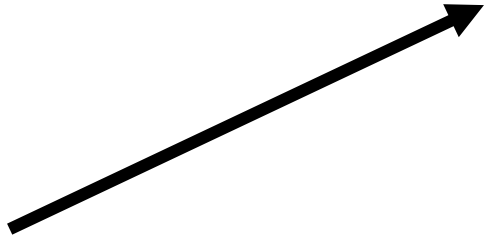


surface list

edge list

vertex list

Reminder: What is a Vector?



- ☑ Does a vector have a ***direction*** ?
- ☑ Does a vector have a ***length*** ?
- ☒ Does a vector have a ***position*** ?
- ☑ Does a vector have an ***orientation*** ?

$$V_1 = \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

Reminder: Product of Vectors

$$V_1 = \begin{pmatrix} a_1 \\ b_1 \\ c_1 \end{pmatrix} \qquad V_2 = \begin{pmatrix} a_2 \\ b_2 \\ c_2 \end{pmatrix}$$

scalar product:

$$V_1 \cdot V_2 = ?$$

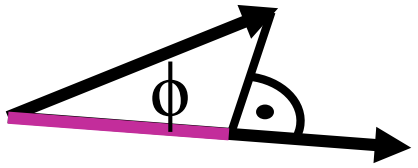
cross product (vector product):

$$V_1 \times V_2 = ?$$

Reminder: Product of Vectors

scalar product:

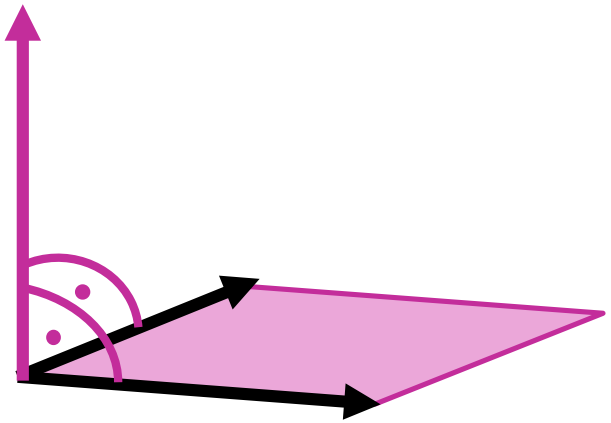
$$V_1 \cdot V_2 = \begin{pmatrix} a_1 \\ b_1 \\ c_1 \end{pmatrix} \cdot \begin{pmatrix} a_2 \\ b_2 \\ c_2 \end{pmatrix} = a_1 a_2 + b_1 b_2 + c_1 c_2$$



$$V_1 \cdot V_2 = |V_1||V_2|\cos\phi$$

cross product (vector product):

$$V_1 \times V_2 = \begin{pmatrix} a_1 \\ b_1 \\ c_1 \end{pmatrix} \times \begin{pmatrix} a_2 \\ b_2 \\ c_2 \end{pmatrix} = \begin{pmatrix} b_1 c_2 - c_1 b_2 \\ c_1 a_2 - a_1 c_2 \\ a_1 b_2 - b_1 a_2 \end{pmatrix}$$

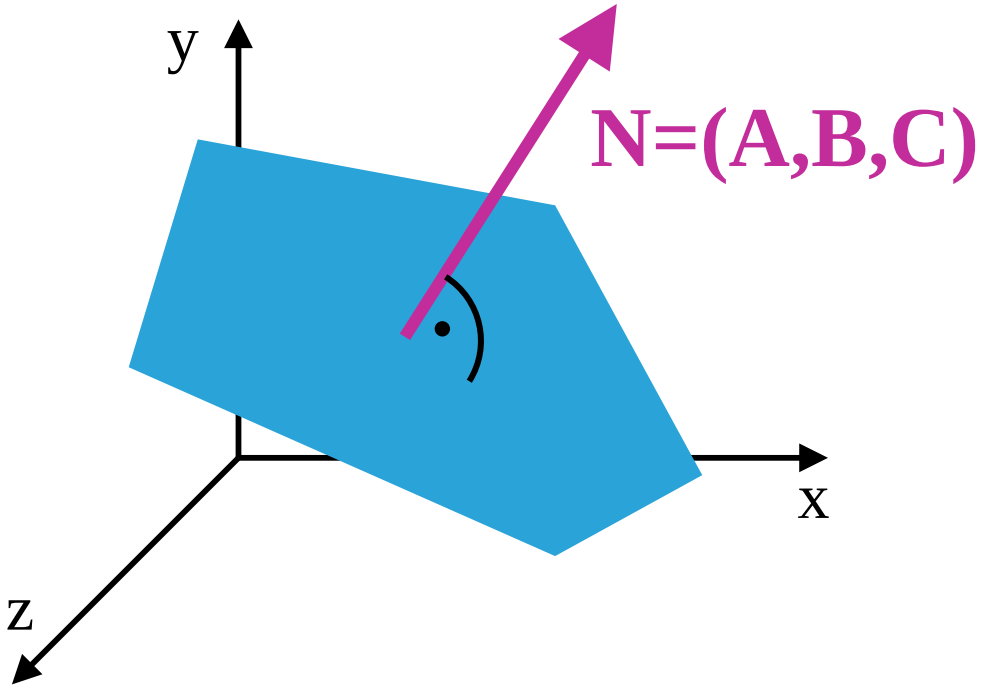


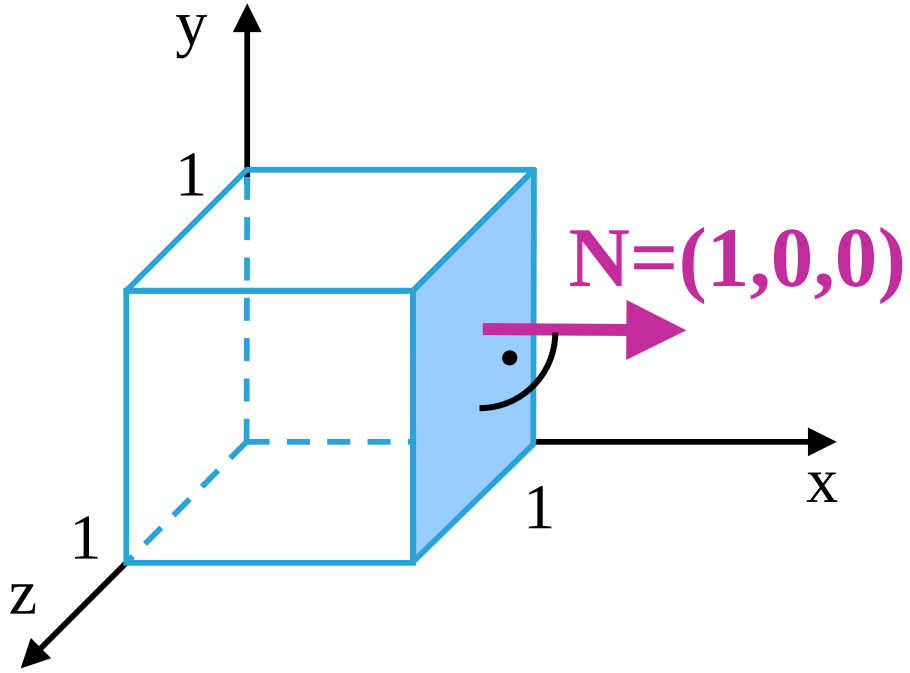
$$|V_1 \times V_2| = |V_1||V_2|\sin\phi$$

Polygon Surfaces: Plane Equation

$$Ax + By + Cz + D = 0$$

- plane parameters **A,B,C,D**
- normal (**A,B,C**)





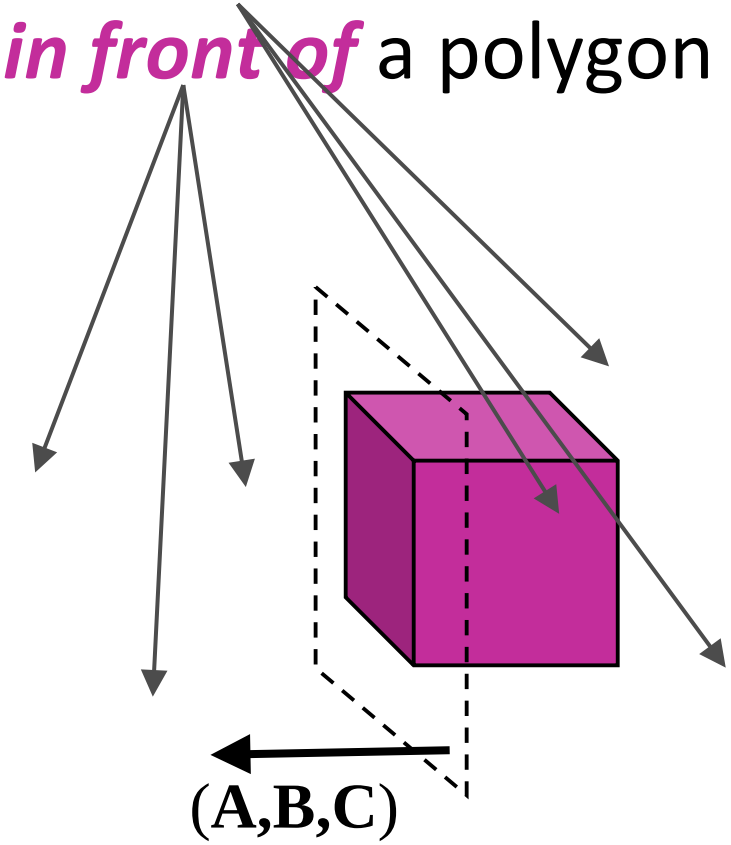
Front and Back Polygon Faces

back face = polygon side that faces into the object interior

front face = polygon side that faces outward

behind a polygon plane = visible to the polygon back face

in front of a polygon plane = visible to the polygon front face



[front = the side to which (A,B,C) points]

Front and Back Polygon Faces

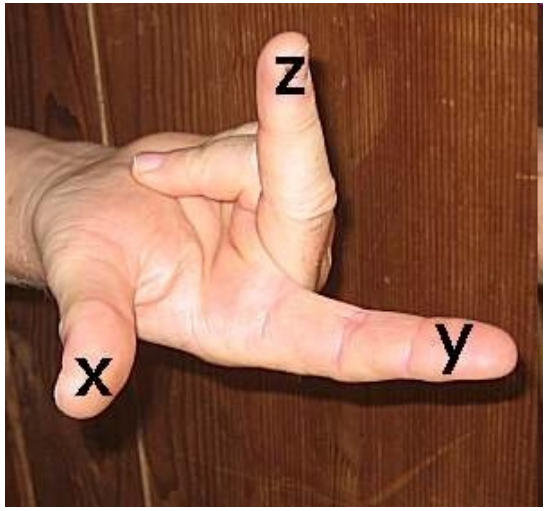
$Ax + By + Cz + D = 0$ for points on the surface

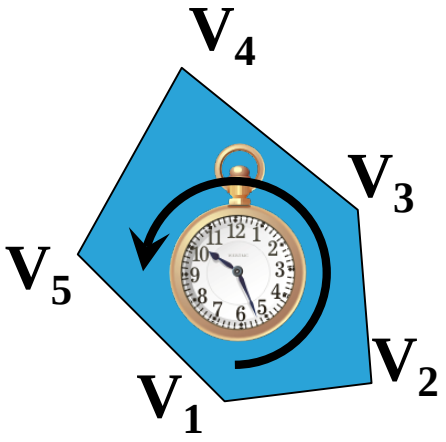
< 0 for points behind

> 0 for points in front

if (1) right-handed coordinate system

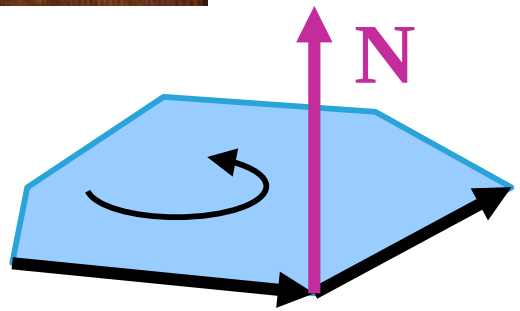
(2) polygon points are ordered counterclockwise





$\mathbf{V_1}, \mathbf{V_2}, \mathbf{V_3}$ counterclockwise $\Rightarrow$

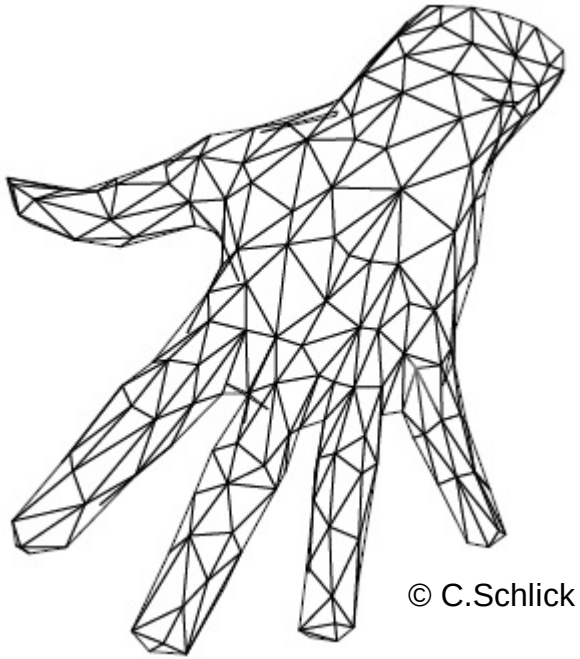
normal vector $\mathbf{N} = (\mathbf{V_2} - \mathbf{V_1}) \times (\mathbf{V_3} - \mathbf{V_1})$



Triangle Meshes

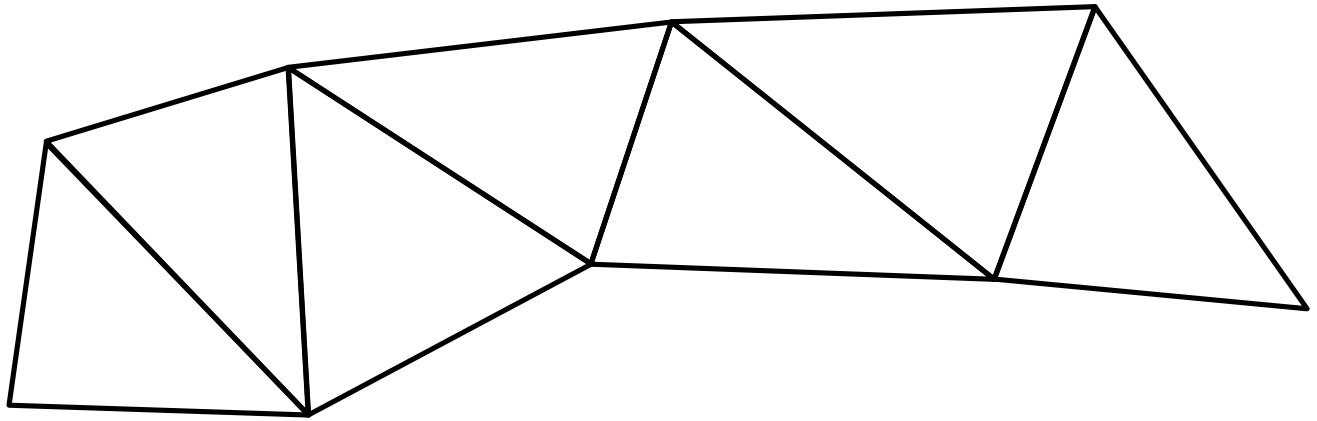
most polygons are triangles

triangle mesh = connected triangles



© C.Schlick

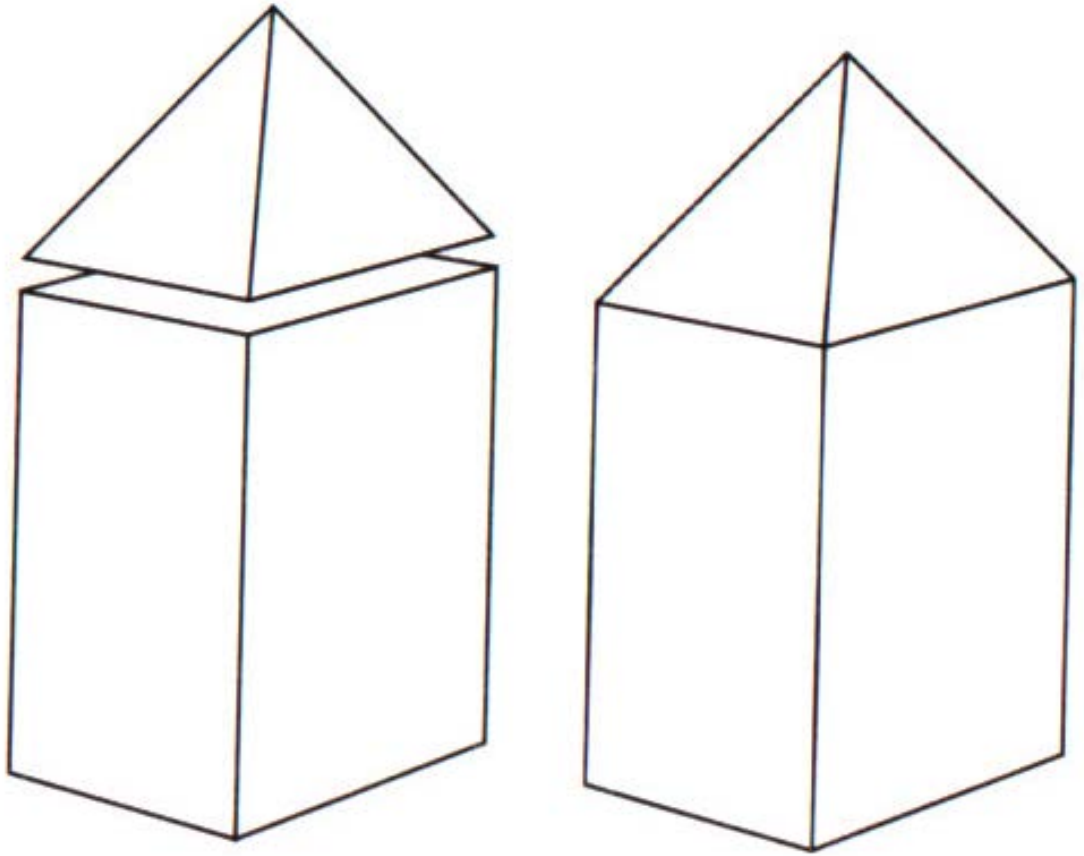
triangle-strip = successive triangles
(1 additional point per triangle)



Constructive Solid Geometry

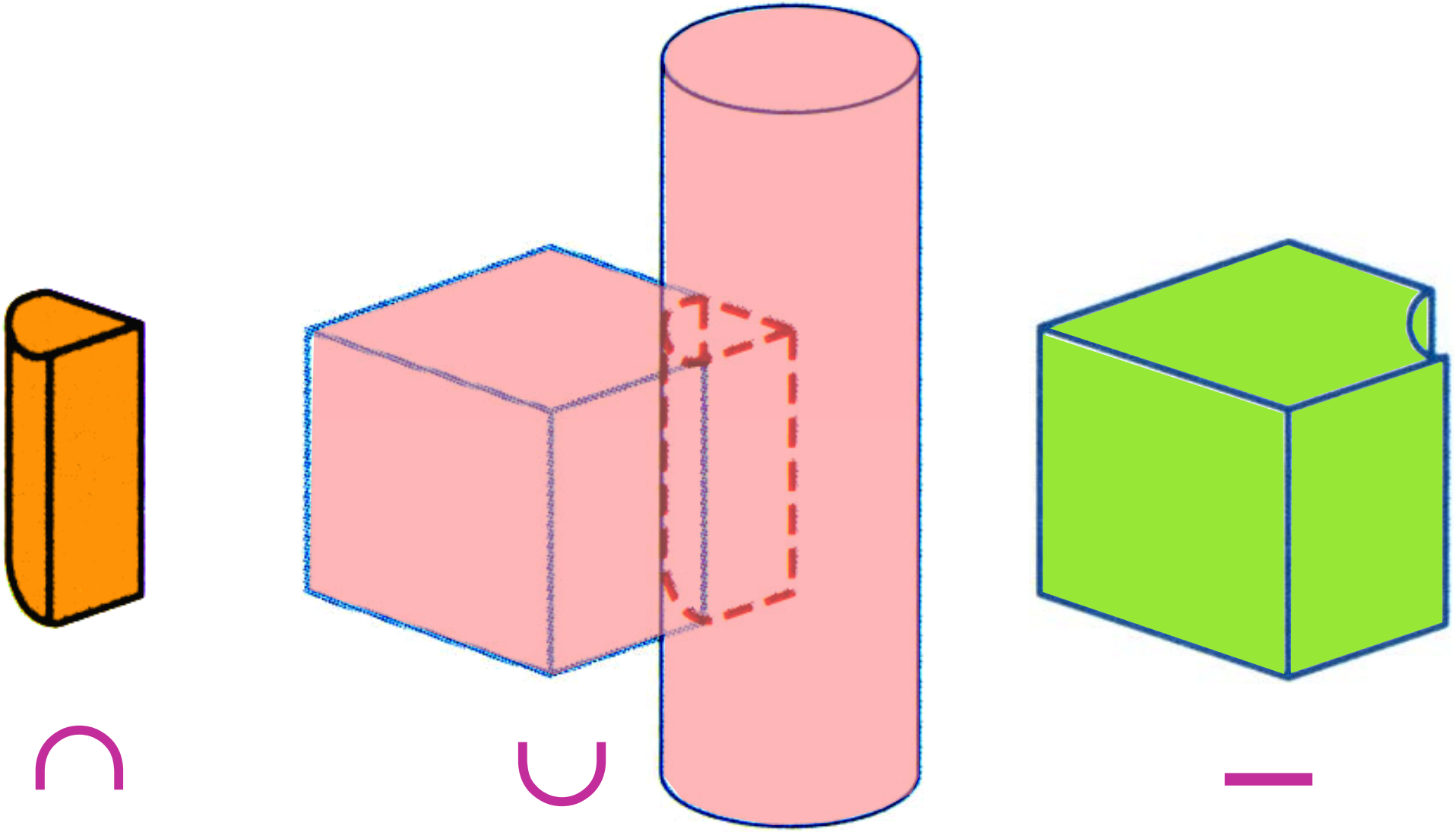
Constructive **S**olid **G**eometry (CSG)

- boolean set operations on 3D objects
- union, intersection, difference operation



combining 2 objects with a union operation, producing a single composite object

CSG: Different Set Operations



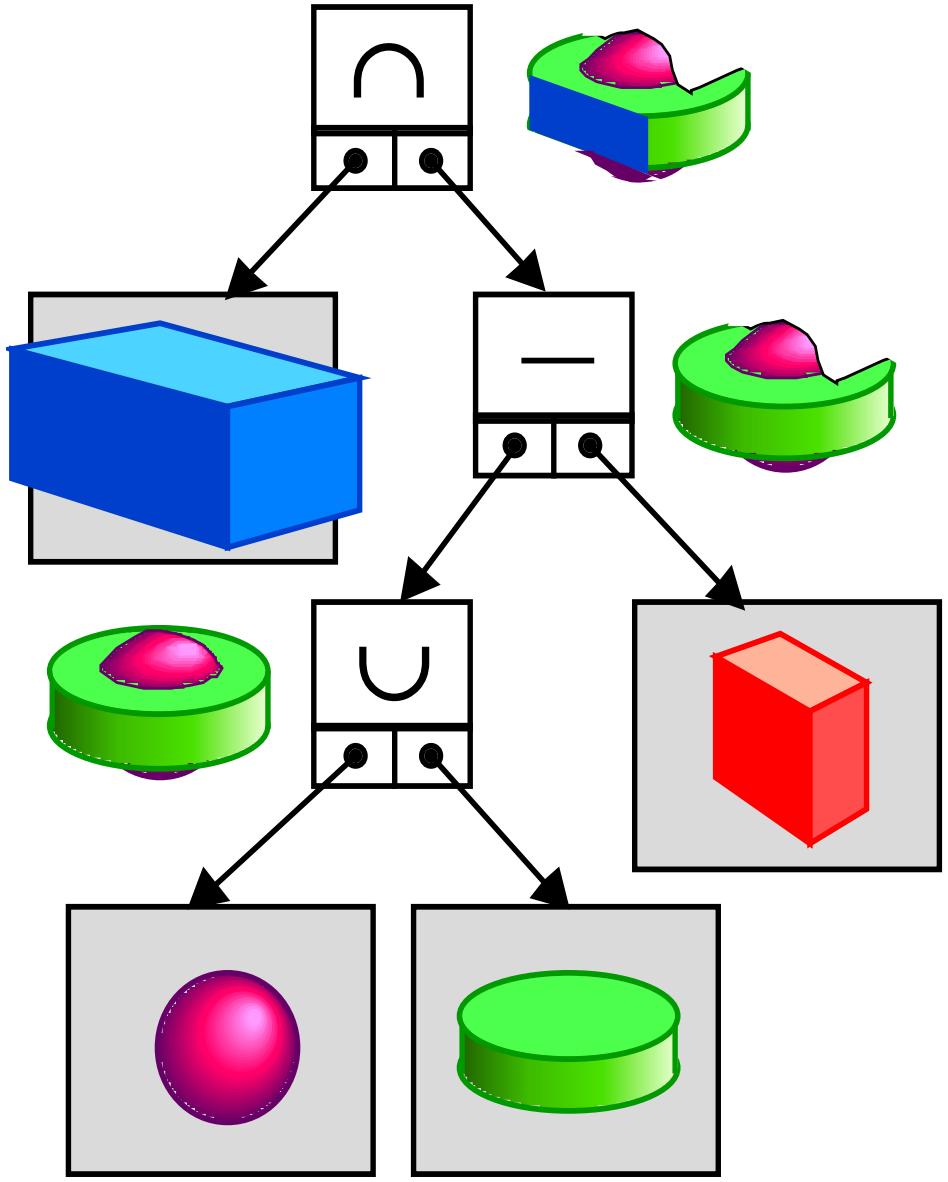
CSG Data Structure

every object is assembled from simple solids with

set operations

data structure: **binary tree**

recursive evaluation



Operations with CSG Trees

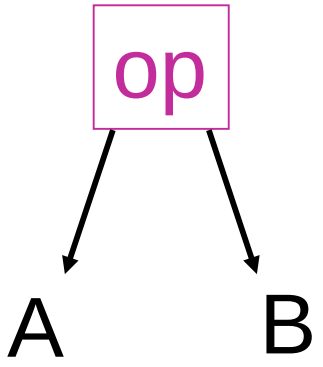
transformations

multiplication of all transformation matrices with the matrix of this transformation

combinations

generate a new node with the desired operator and link the operands as subtrees to it

A op B:



Rendering of CSG Trees

transform into B-Rep and use normal hidden surface algorithm

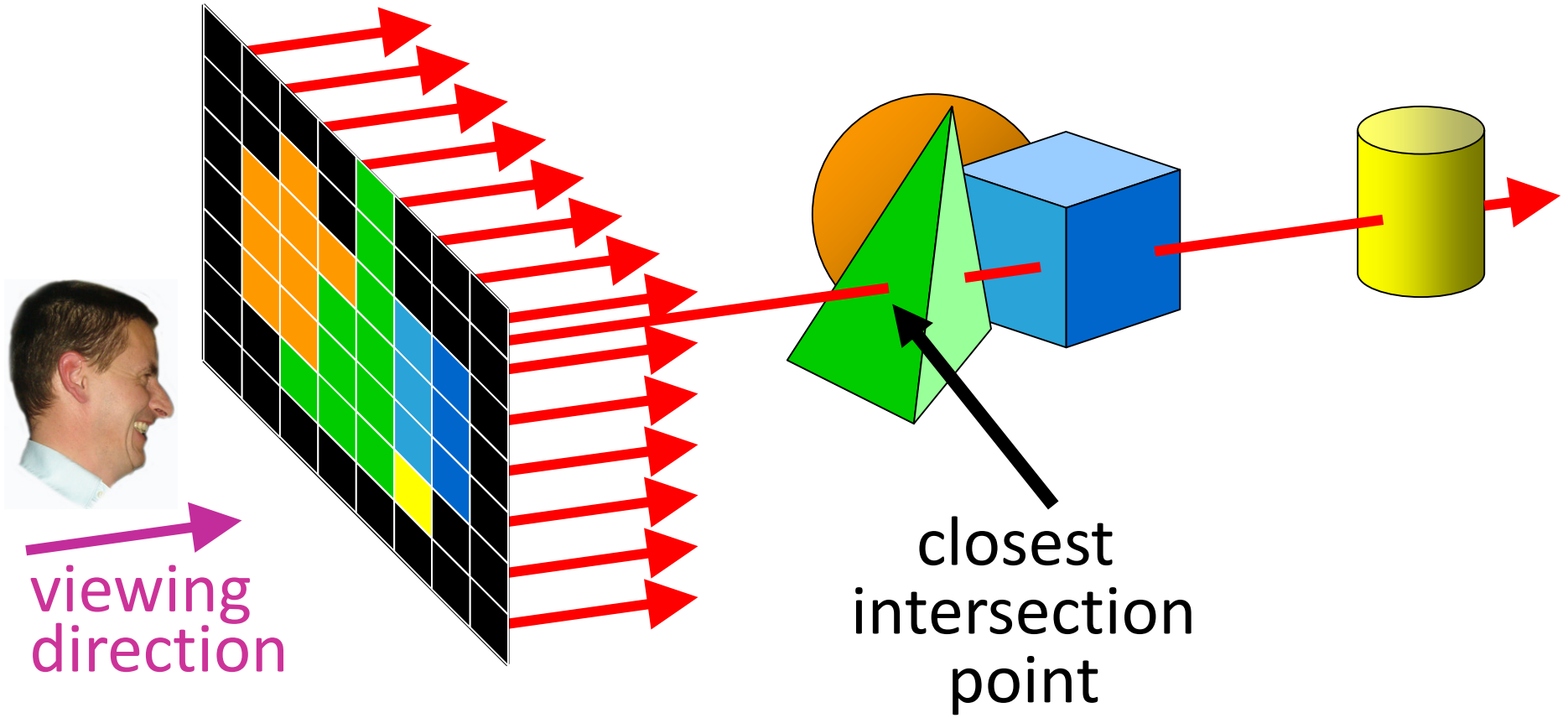
or

render directly with ray casting (or with ray tracing)

Ray-Casting Method (1)

line-of-sight of each pixel is intersected with all surfaces

→ take closest intersected surface



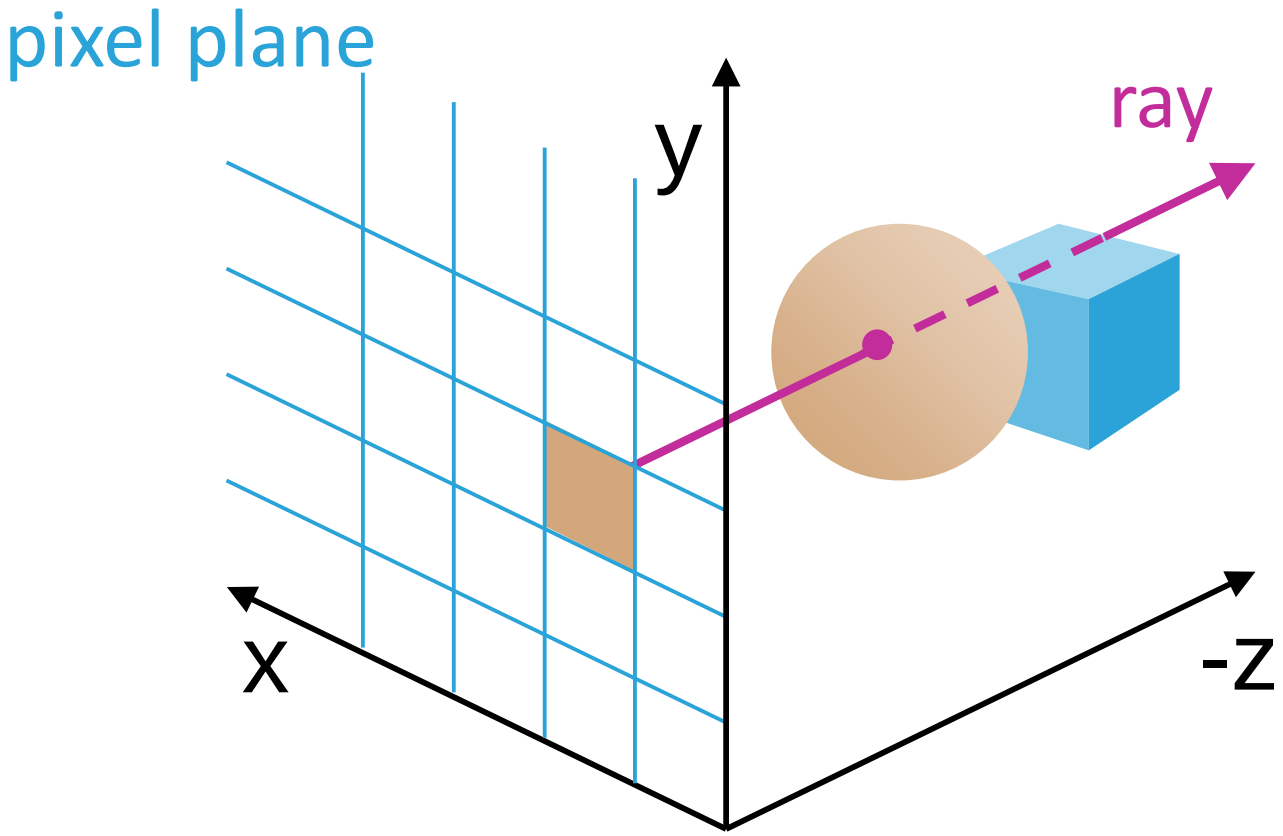
Ray-Casting Method (2)

- based on geometric optics, tracing paths of light rays
- backward tracing of light rays
- suitable for complex, curved surfaces
- special case of ray-tracing algorithms
- efficient ray-surface intersection techniques necessary

  → intersection point & normal vector needed

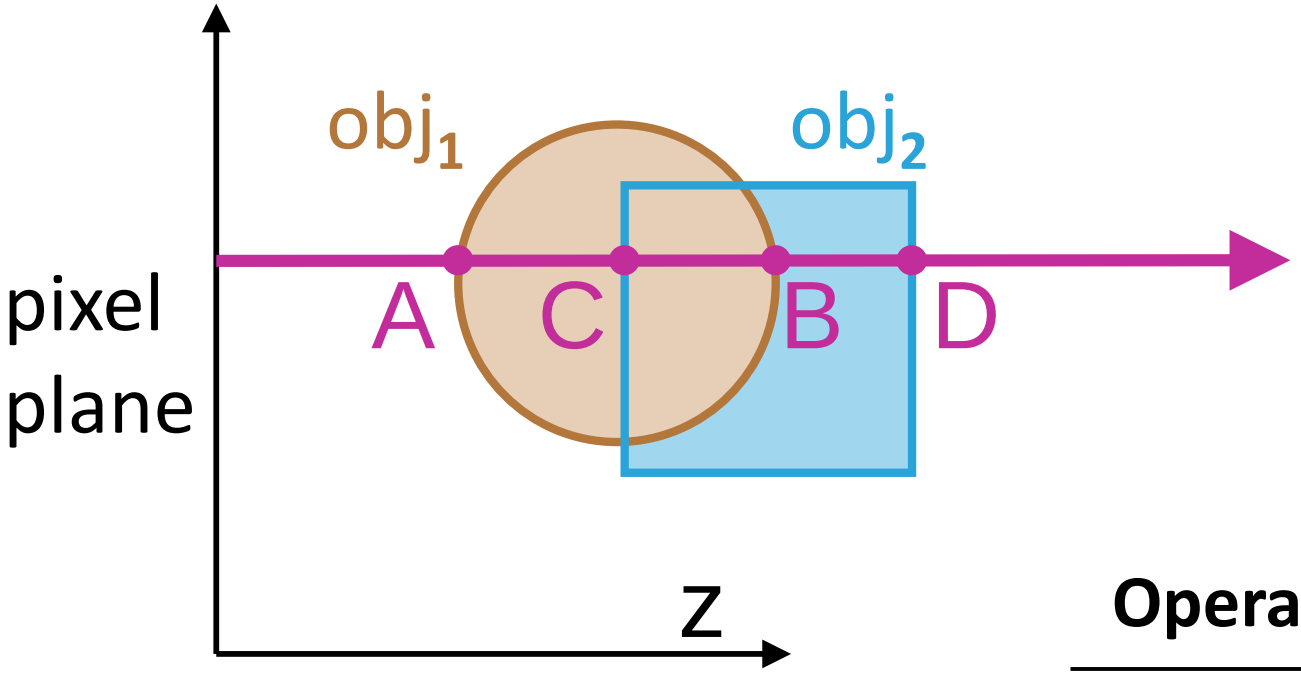
Ray-Casting Methods for CSG (1)

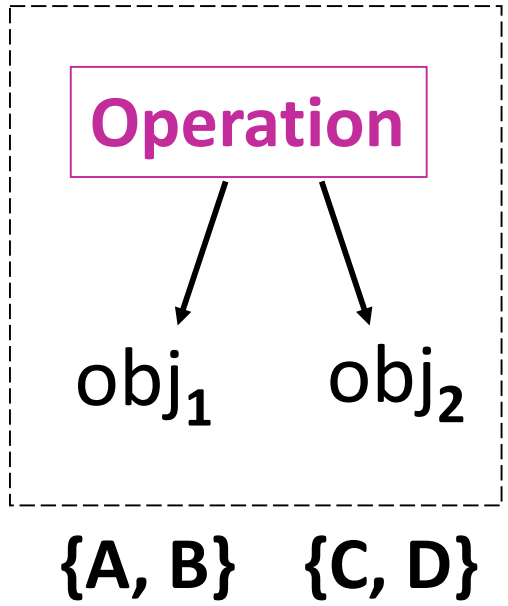
visibility processing



Ray-Casting Methods for CSG (2)

determining surface limits



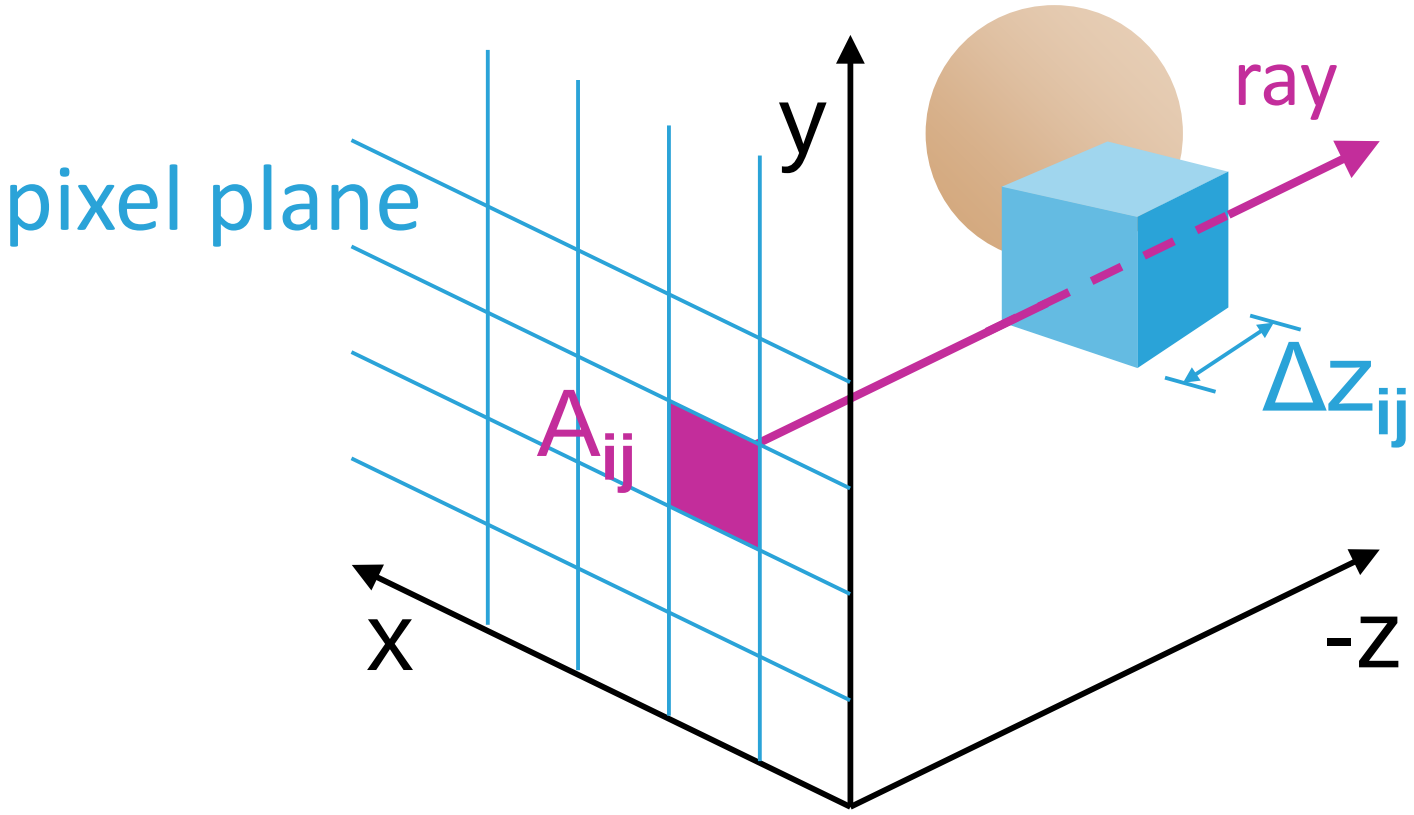


Operation	Result
Union	{A, D}
Intersection	{C, B}
Difference	{A, C}

Ray-Casting Methods for CSG (3)

volume determination

$$V_{ij} \approx A_{ij} \cdot \Delta z_{ij} \qquad V \approx \Sigma V_{ij}$$



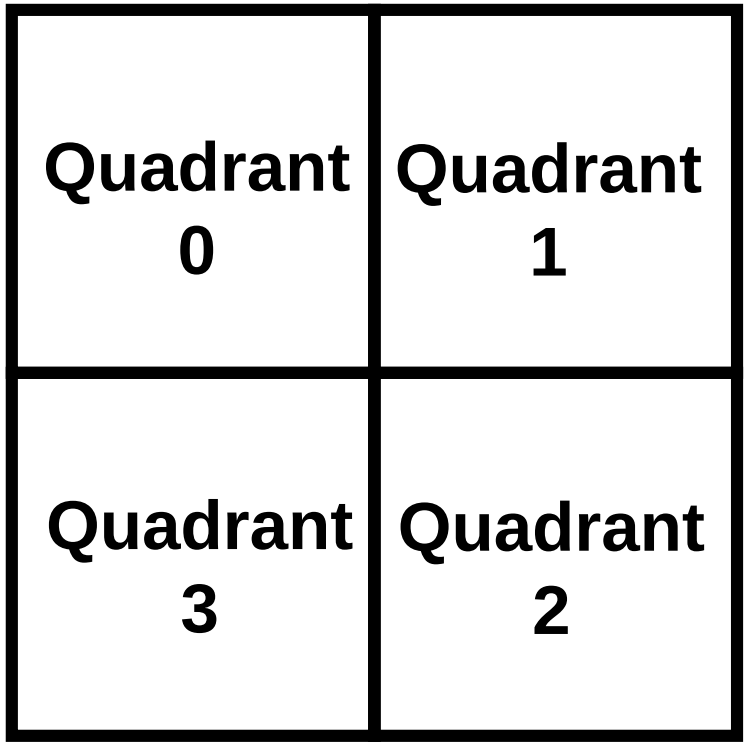
Properties of CSG

- advantages
  - exact representation
  - low memory cost
  - combinations and transformations trivial

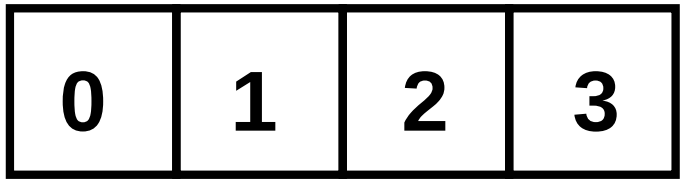
- disadvantages
  - rendering effort is high

Quadtrees

- hierarchical enumeration of objects
- in 2D: quadtree
  - hierarchical subdivision until a region is homogeneous



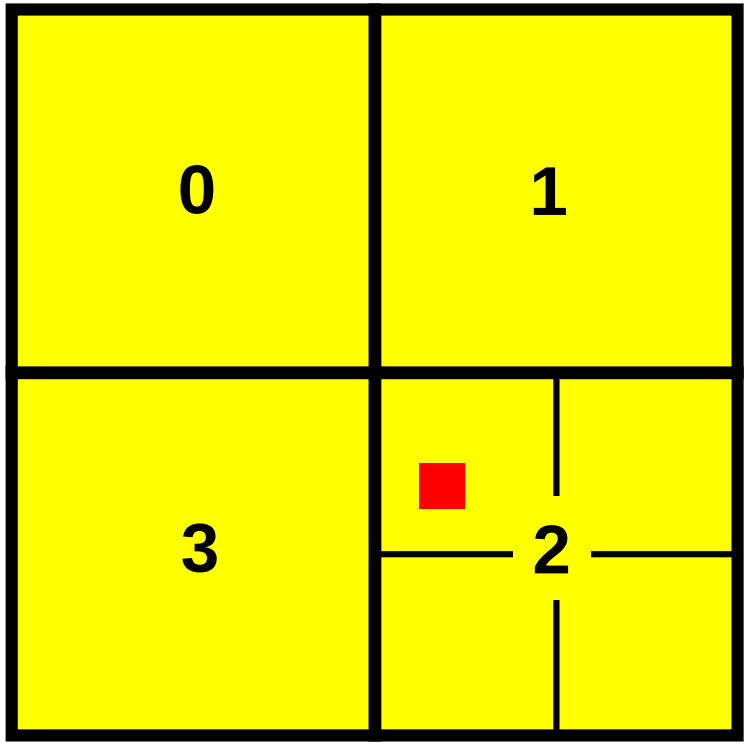
region of a 2-dim. space

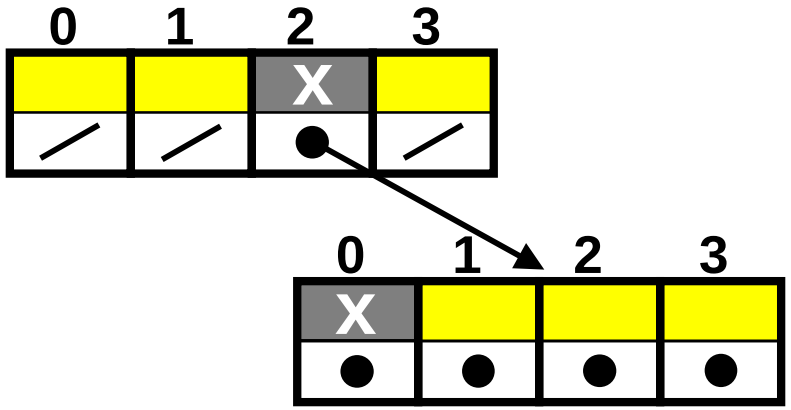


data elements in the representative quadtree node

Quadtrees

- area with 2^n by 2^n pixels $\Rightarrow$ quadtree with n levels
- storage efficient





Quadtrees

- area with 2^n by 2^n pixels $\Rightarrow$ quadtree with n levels
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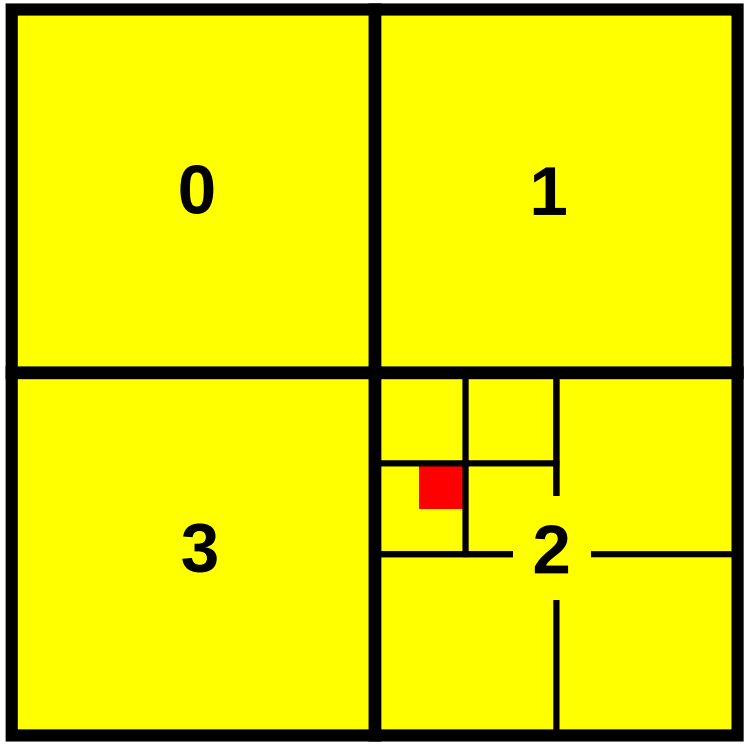

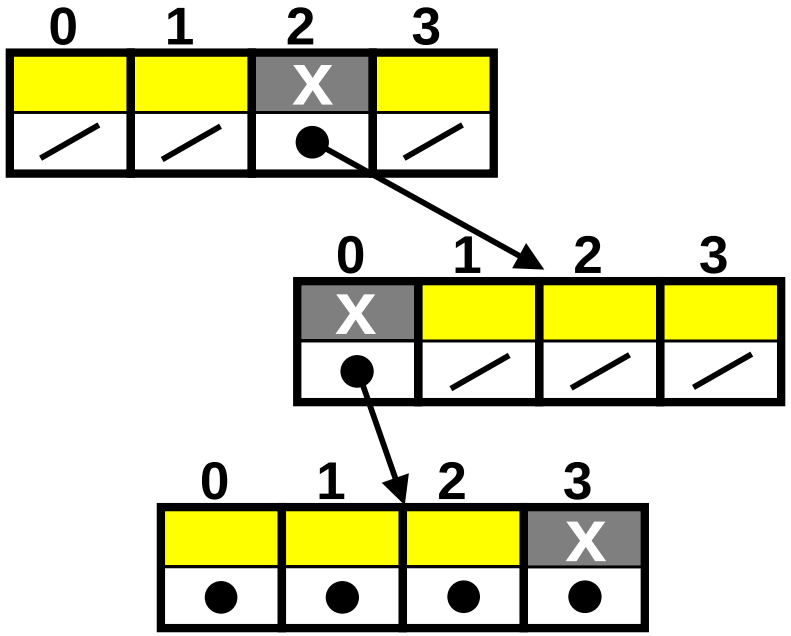

Quadtrees

- area with 2^n by 2^n pixels $\Rightarrow$ quadtree with n levels
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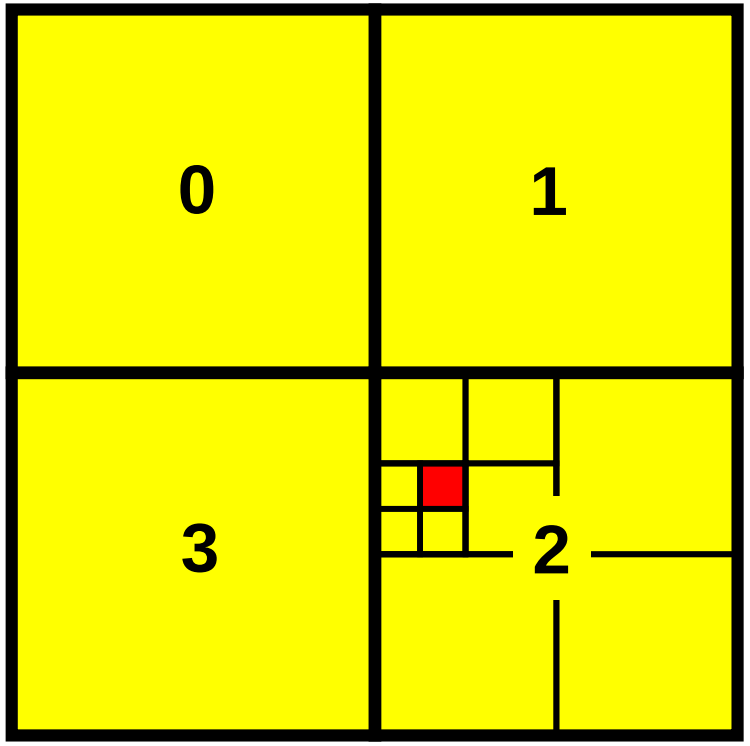
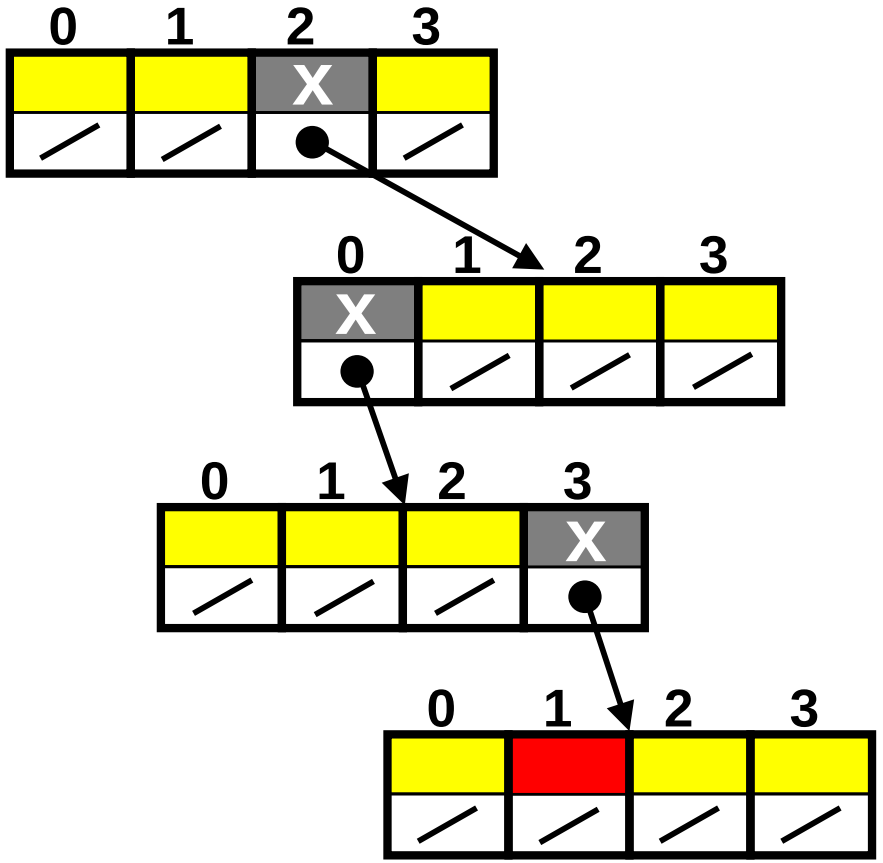
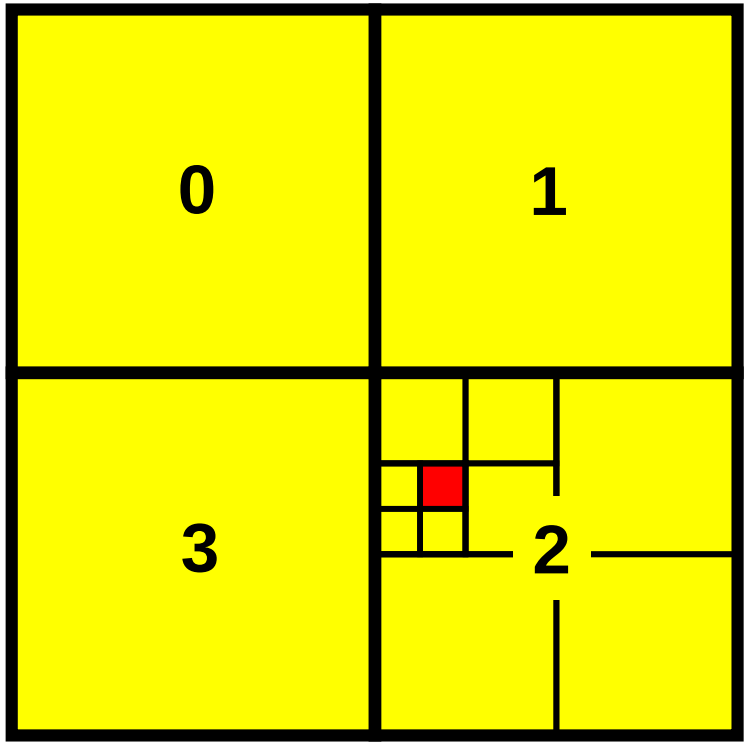
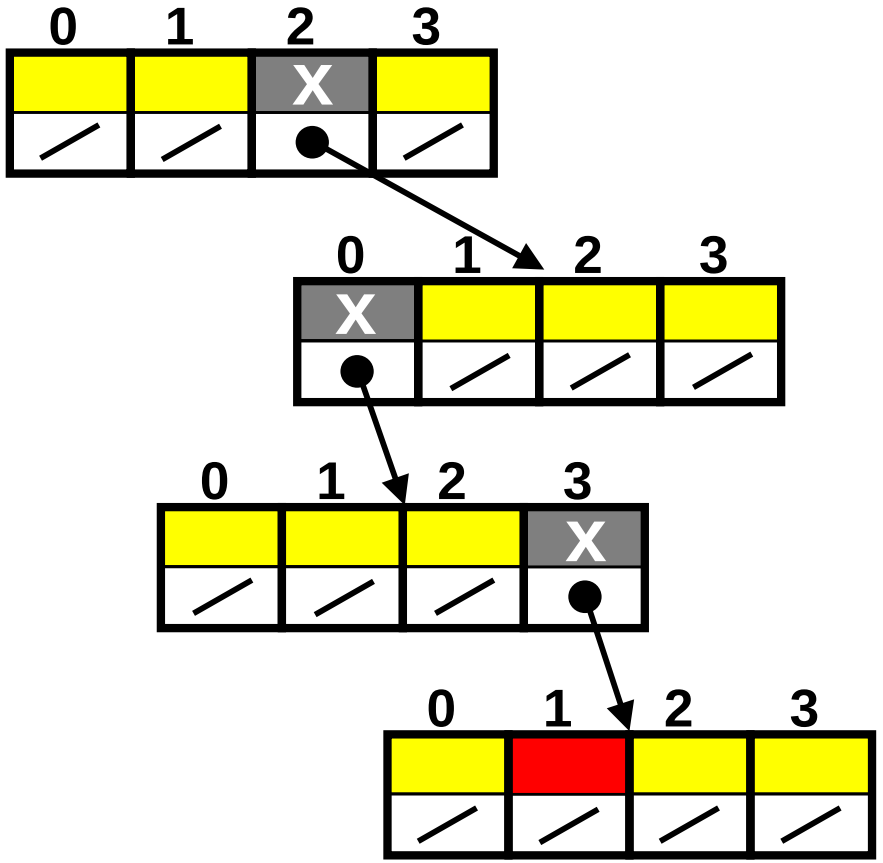




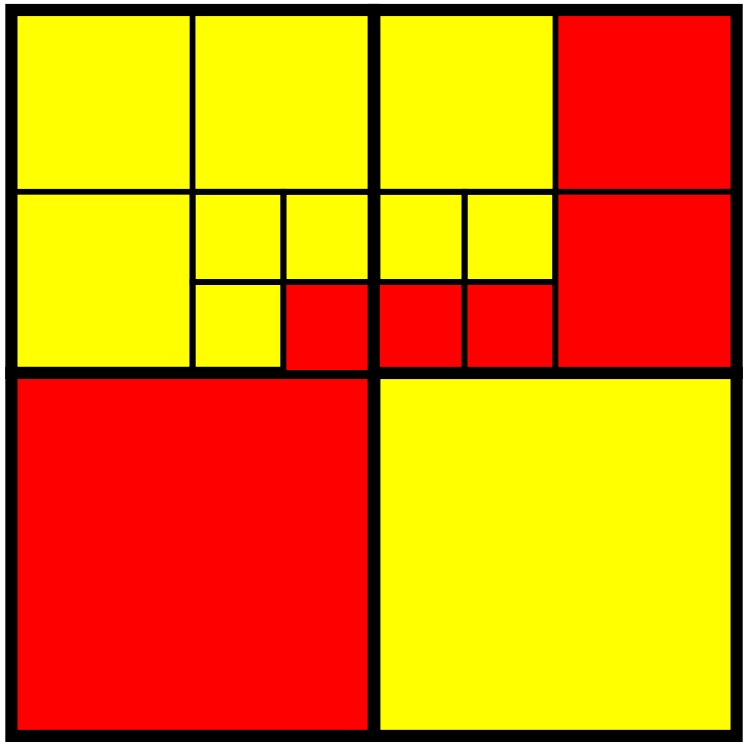
Quadtrees

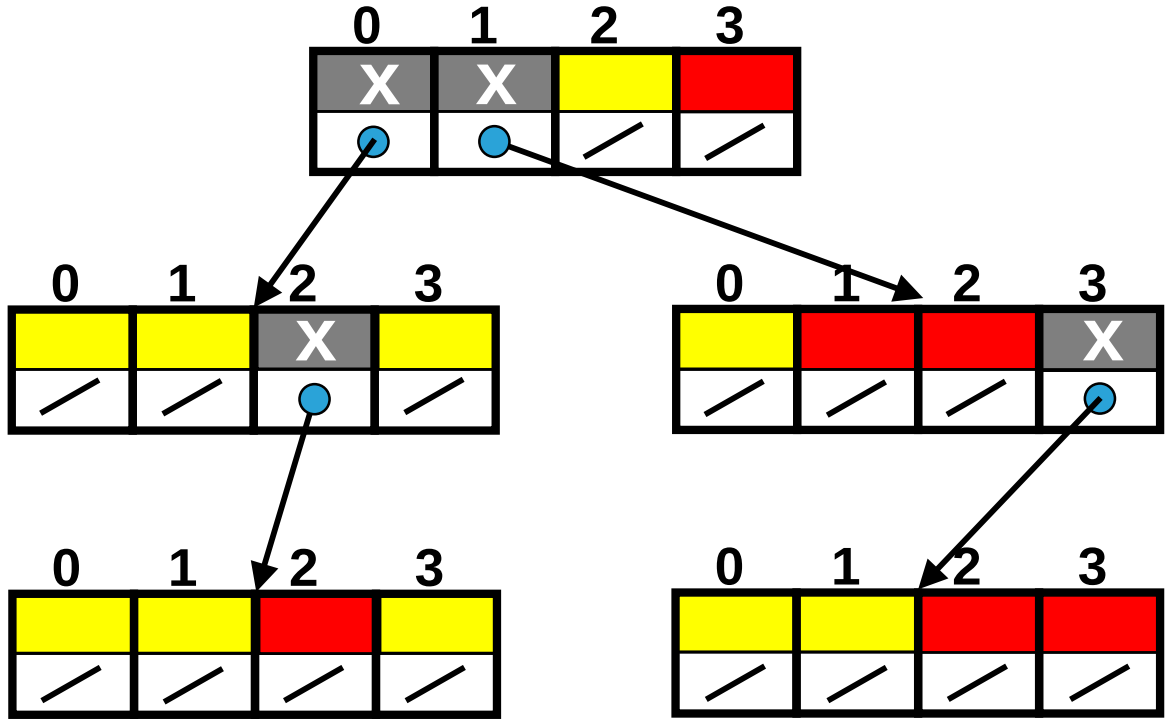
quadtree representation for a region containing one green foreground-color pixel on a yellow solid background





Quadtree Example

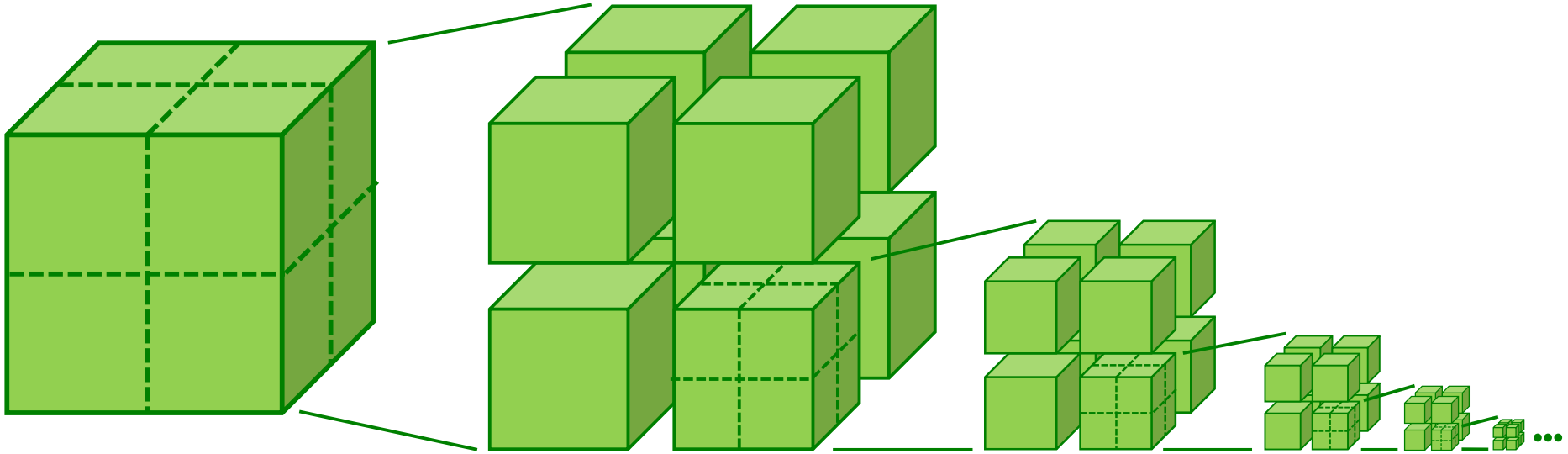




suitable for representing (2D) images

Octree

= extension to 3D

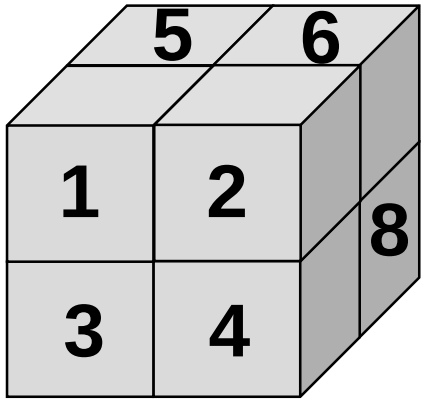


regular space subdivision:

- simple (empty or uniform) ⇒ leaf node
- complex (other cases) ⇒ divide further

Octrees

- octree divides 3D cube into octants
- volume elements (voxels)
- set operations easy on octrees
- geometric transformations difficult on octrees

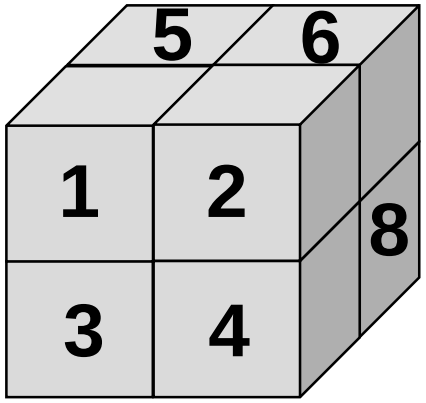


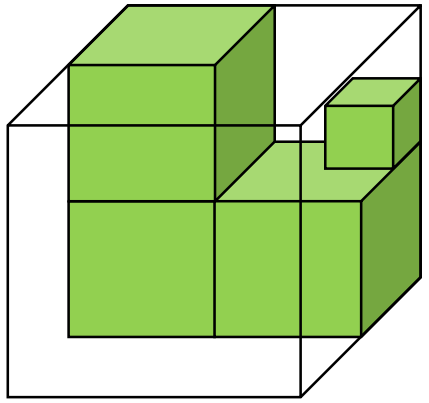
region of a 3-dim. space

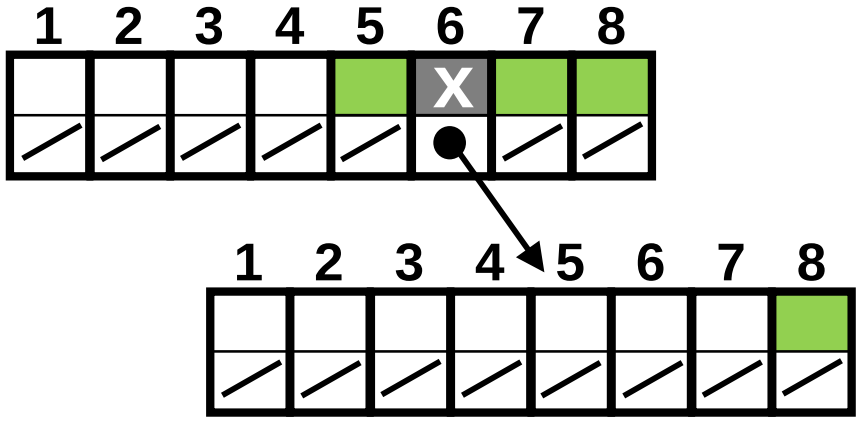
1	2	3	4	5	6	7	8

data elements in the representative octree node

Octree Very Simple Example







linearization: X(EEEESX(EEEEEEES)SS)

E … Empty, S … Solid, X … Mixed

Operations with Octrees

transformations

very complicated except for a few special cases,
e.g. rotation by 90°, mirroring at a subdivision plane, scalation by 2^n

combinations

very simple:
if A or B homogeneous $\Rightarrow$ simple rules
else combine recursively all 8 octants of A and B

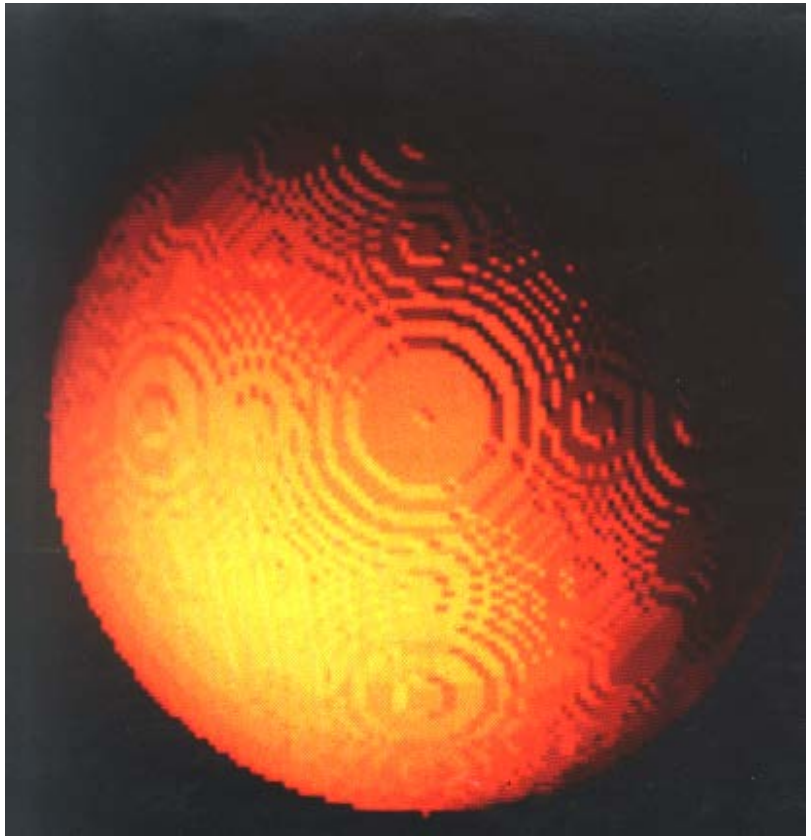
Properties of Octrees

advantages

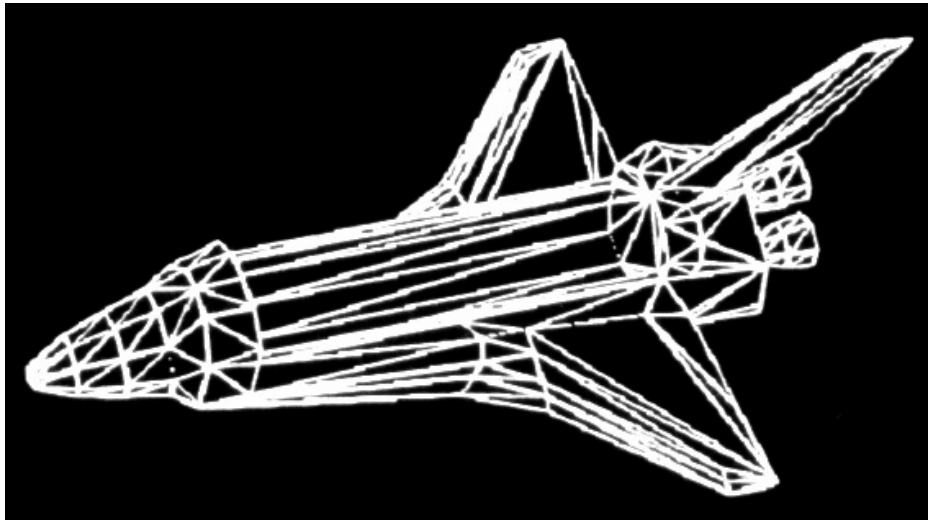
- combinations very simple
- fast rendering
- spatial search possible

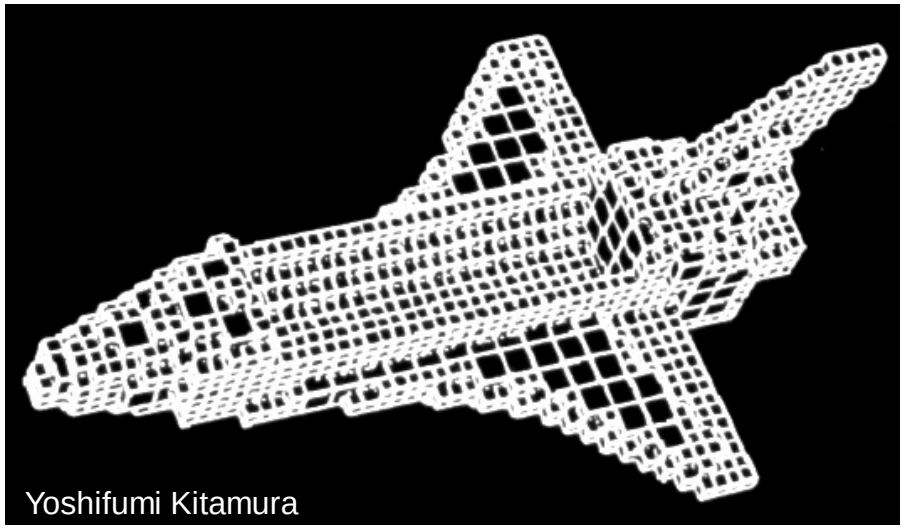
disadvantages

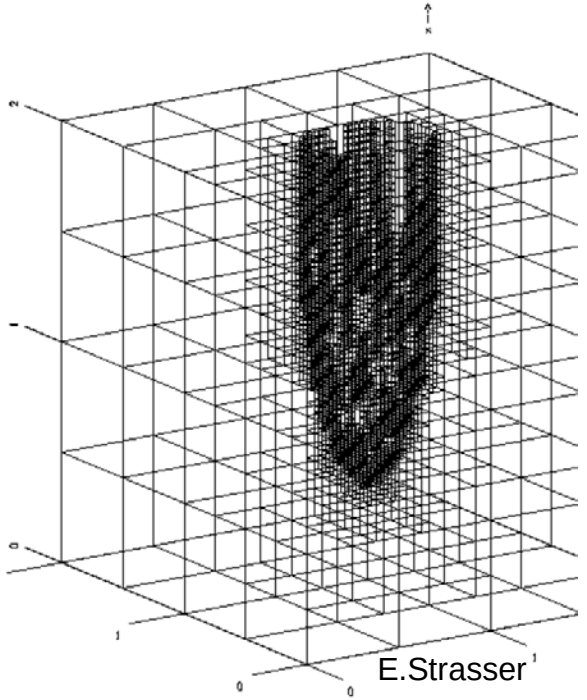
- inexact representation
- low image quality
- restricted transformations
- high memory cost

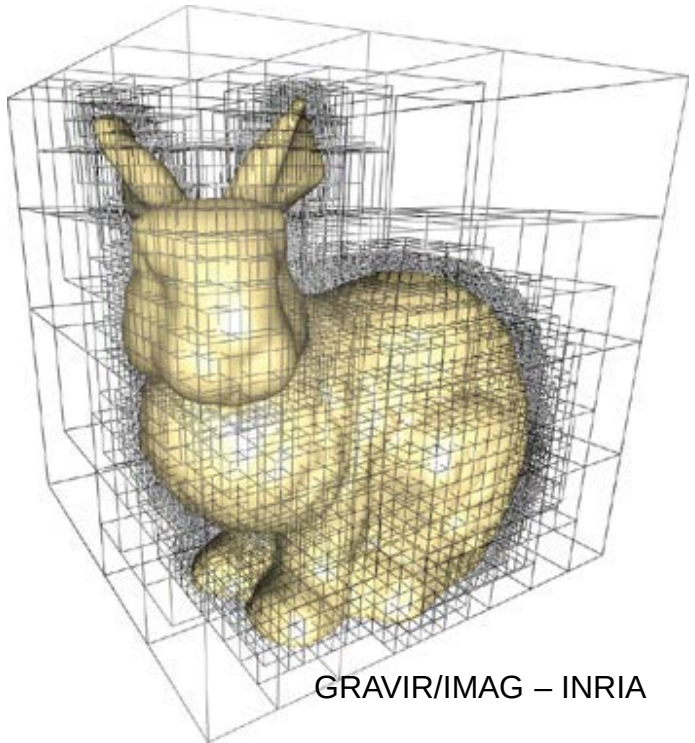


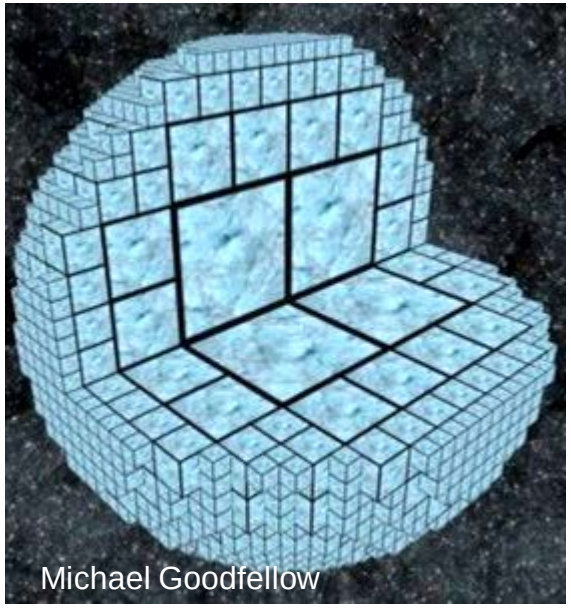
Octree Examples











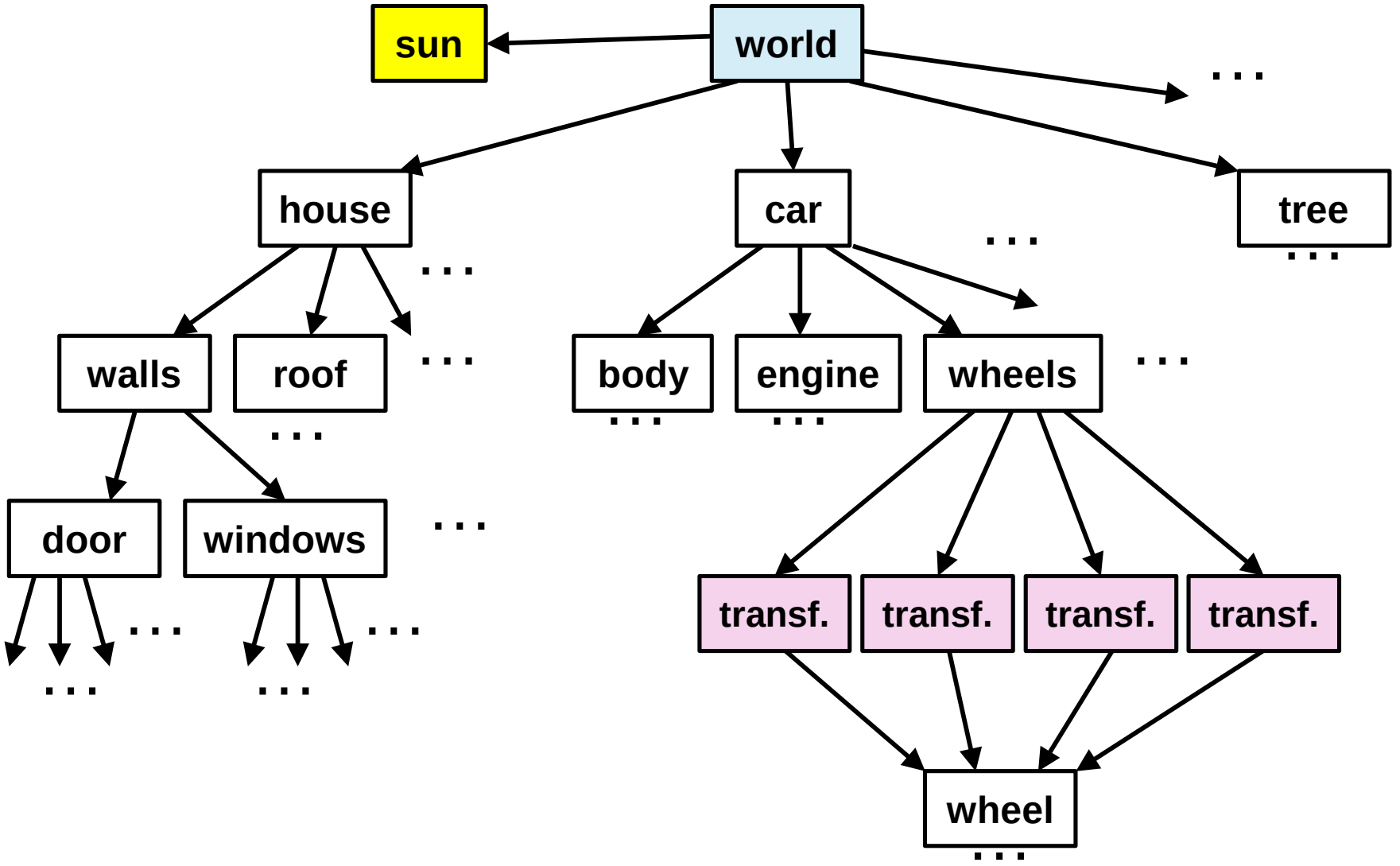
Other 3D Object Representations

- BSP trees
- fractal geometry methods
- shape grammars, procedural models
- particle systems
- physically based modeling
- visualization of data sets
- ...

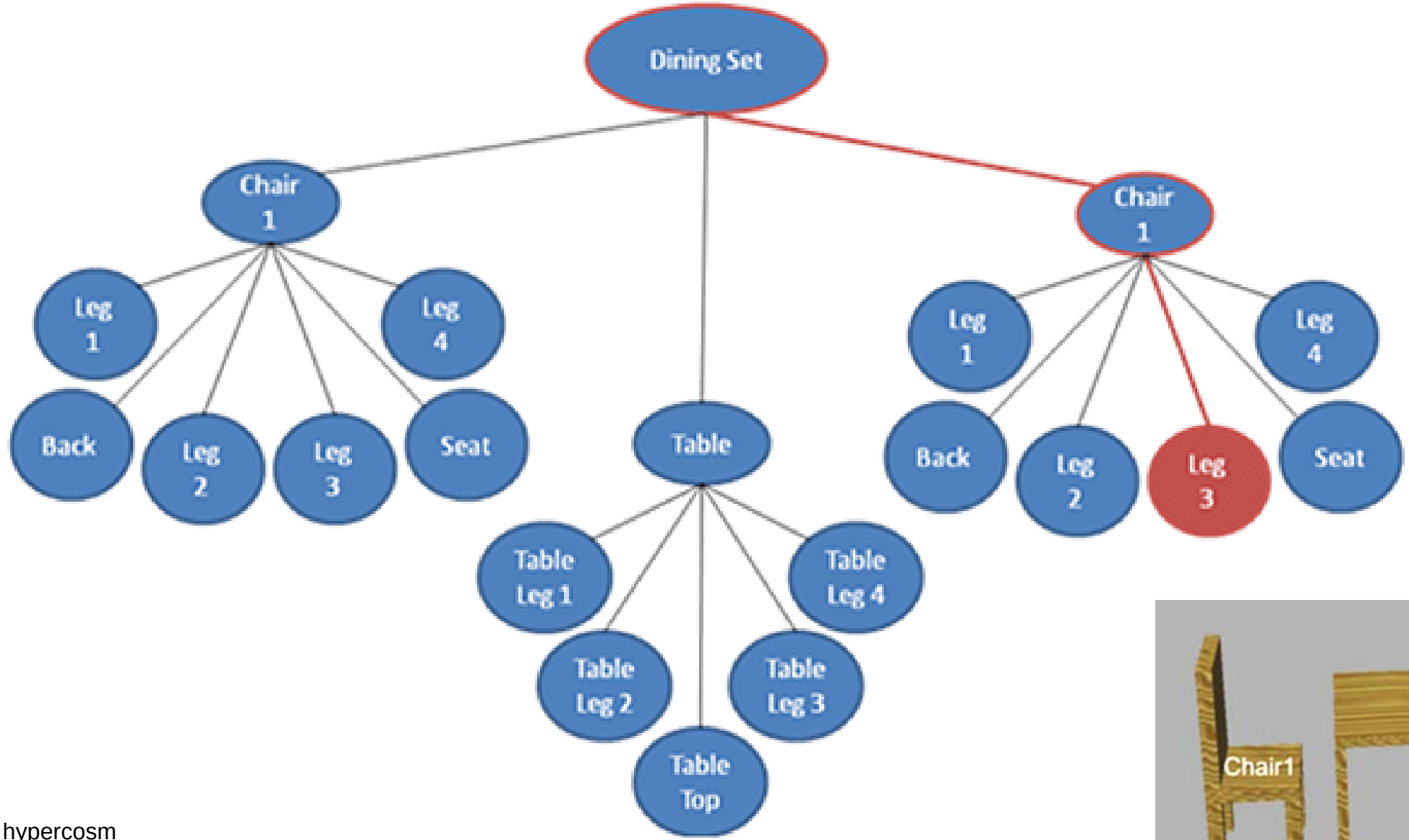
Scene Graphs

- object-oriented data structure
  - directed acyclic graph
- describes logical and/or spatial relationship of scene objects
- describes groups of (groups of …) objects
- no exact definition
- used in most graphics systems, e.g.
  - OpenSceneGraph
  - VRML
  - X3D …

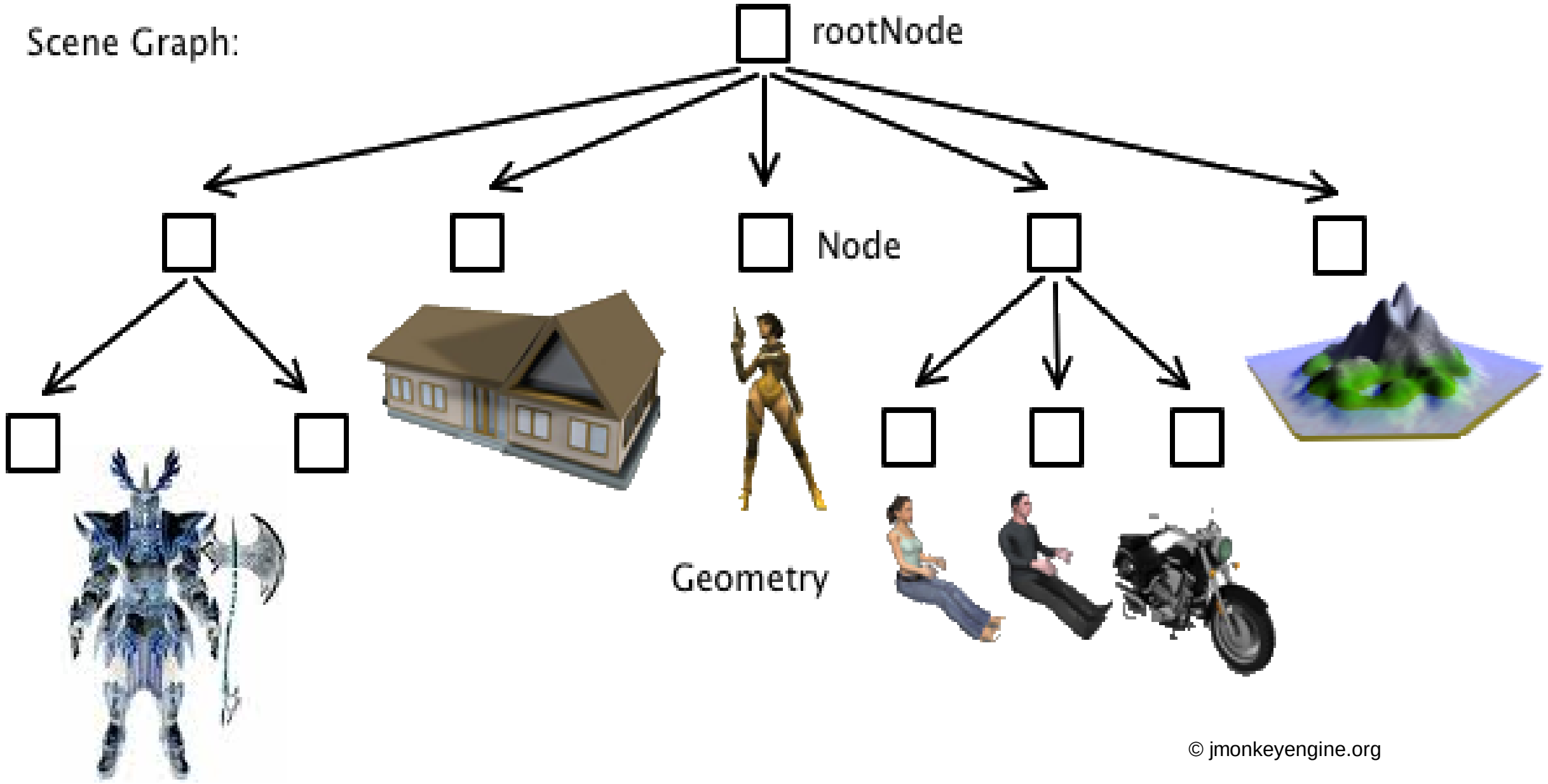
Scene Graph Example



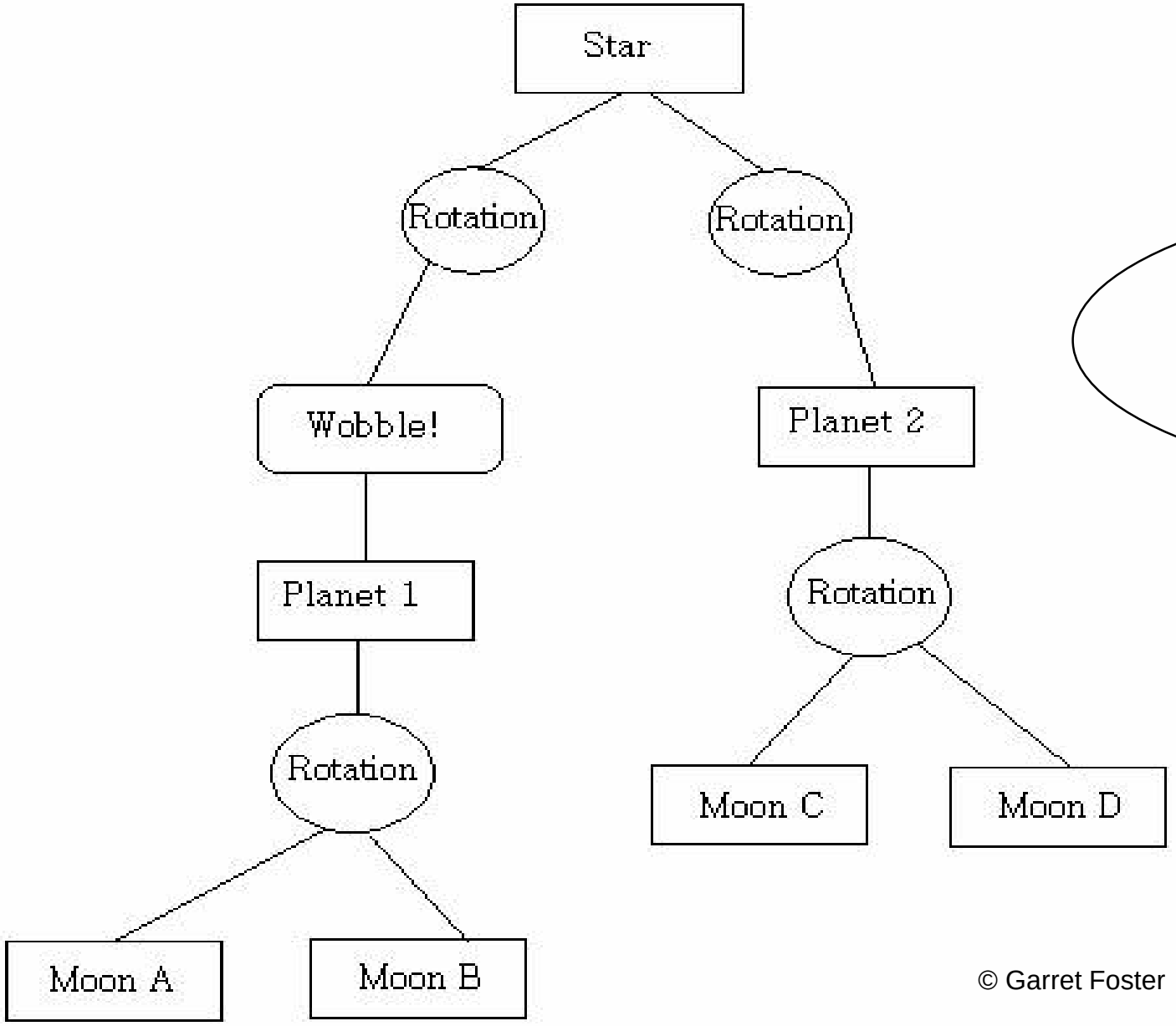
Scene Graph Example

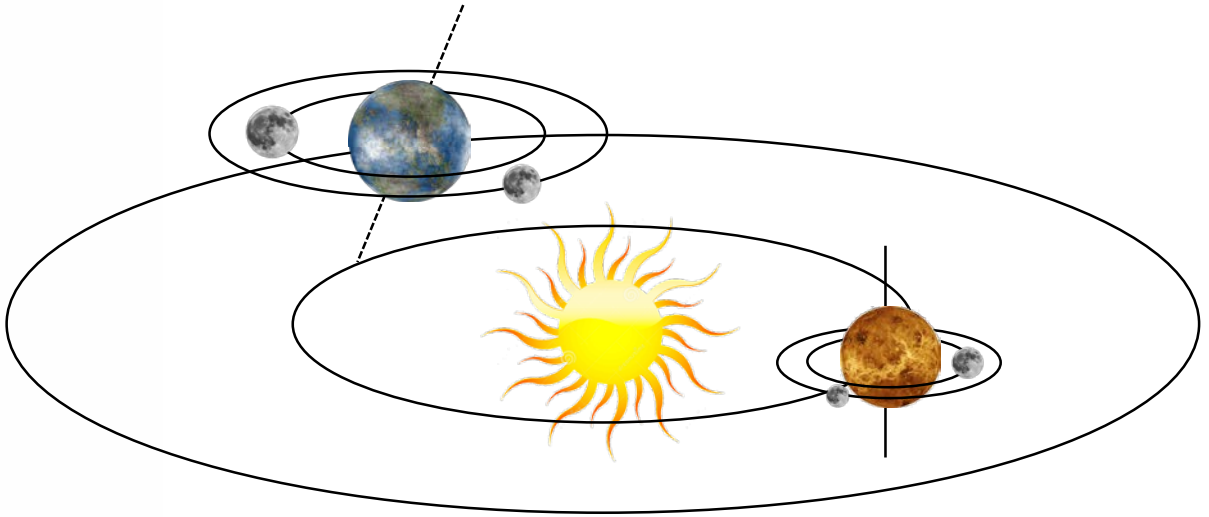


Scene Graph Example

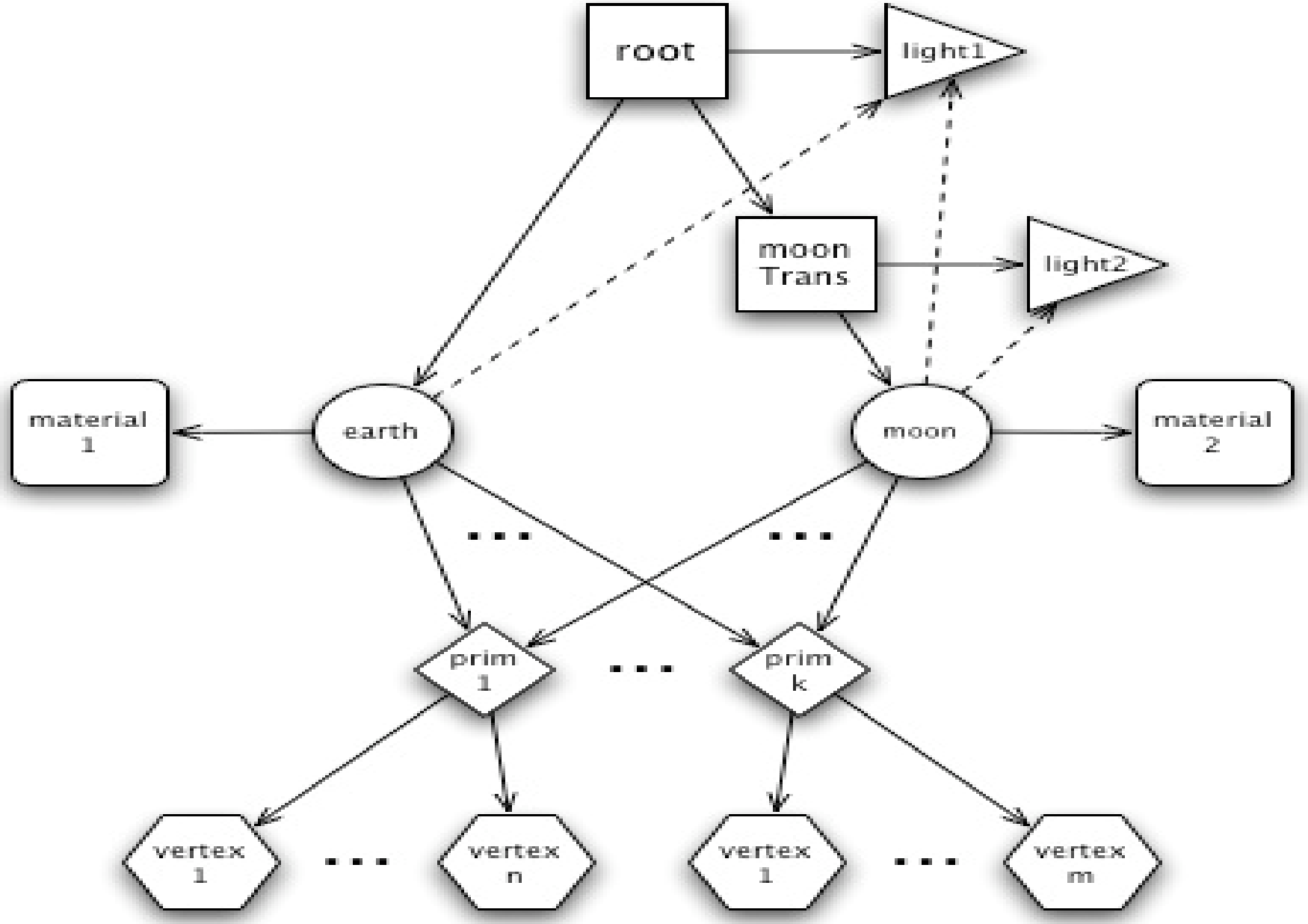


Scene Graph Example

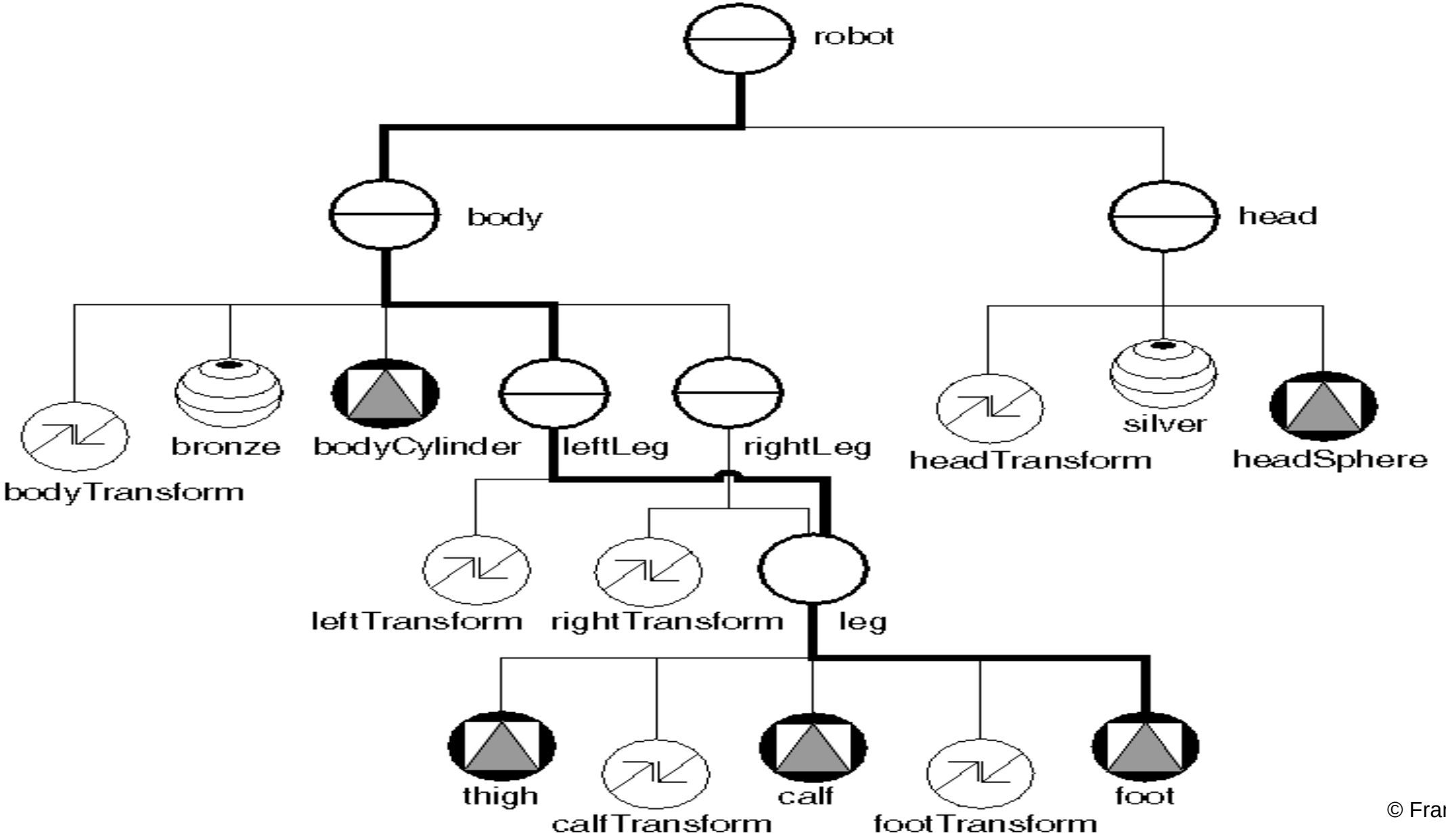




Scene Graph Example



Scene Graph Example



Scene Graph Example